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Advanced Tensiometer Monitoring Results from the Deep Vadose Zone at the Radioactive Waste Management Complex

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Bechtel BWXT Idaho, LLC

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ABSTRACT

A network of 30 advanced tensiometers in 18 wells provided field water potential data to monitor moisture conditions and movement in the subsurface beneath and adjacent to the Subsurface Disposal Area (SDA), at depths ranging from 6.7 to 73.5 m below land surface. Long-term water potential data were evaluated to determine the appropriateness of the current conceptual flow model at the Radioactive Waste Management Complex. In general, water potentials ranged from near saturation (-30 cm of water) in the 34-m sedimentary interbed to -400 cm of water in the 73-m sedimentary interbed. In the near surface basalts and sediments (less than 12 m below land surface) drying trends were observed in response to the cumulative effect of less-than-average annual precipitation for the last three years (2000 through 2002). Water potential data from the majority of the deeper tensiometers (17 m or greater) indicated little-to-no change in moisture, suggesting near-steady state conditions at those locations for the past 2-1/2-year-monitoring period. Long-term drying trends in deeper (17 m or greater) sediments were observed at some well locations near drainage ditches that border the main east-west road in the SDA. Drainage ditches likely focused infiltration during years of high run-off from snowmelt. The long-term drying trends may be in response to decreased run-off from the past three years of low precipitation. No episodic recharge events were recorded at these monitoring locations during the spring 2000 through August 2002 time period. Averaged water potentials in the BC interbed suggested wetter conditions inside the SDA as compared to outside the SDA. This was attributed to focused infiltration in low-lying areas, such as in drainage ditches, or open pits and trenches that flooded in the past. The unit gradient method was used to calculate deep percolation and estimates ranged from 1 to 32 cm/yr. These percolation estimates appeared to be reasonable, given the average annual precipitation of 22 cm, the potential for focused infiltration on the SDA, and the simplifying assumptions used to estimate deep percolation.

CONTENTS

FIGURES

TABLES

ACRONYMS

bls	below land surface
INEEL	Idaho National Engineering and Environmental Laboratory
OU	operable unit
PVC	polyvinyl chloride
RWMC	Radioactive Waste Management Complex
SDA	Subsurface Disposal Area
USGS	United States Geological Survey

Advanced Tensiometer Monitoring Results from the Deep Vadose Zone at the Radioactive Waste Management Complex

1. INTRODUCTION

A network of advanced tensiometers at depths ranging from 6.7 to 73.5 m below land surface (bls) beneath and adjacent to the Subsurface Disposal Area (SDA) was monitored to characterize moisture movement at the Radioactive Waste Management Complex (RWMC). Advanced tensiometers are instruments that measure water potential at depths greater than the maximum operating depths of standard tensiometers (9 m). Water potential is related to moisture content and can be used to infer subsurface moisture movement. The monitoring was performed in support of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) remedial investigation/feasibility study (RI/FS) decision process for Waste Area Group (WAG) 7, Operable Unit (OU) 7-13/14 (Holdren et al. 2002), and supports the following objectives:

- Provide in situ field data to augment, confirm, or change the current conceptual model of flow in the unsaturated zone beneath the RWMC
- Provide field water potential data for hydrologic flow model calibration and prediction
- Provide baseline water potential data in vadose zone basalts and sedimentary interbeds in the RWMC area, before remediation and closure of the SDA
- Assess lateral movement of water from the spreading areas in conjunction with planned tracer tests.

The second and third objectives are straightforward. The past 2-1/2 years of data collection from advanced tensiometers at the RWMC have addressed those objectives. Advanced tensiometer monitoring has provided baseline water potential data from sedimentary interbeds and basalts that can be used to help assess the remediation and closure of the SDA. This same activity has also provided field data that can be used for hydrologic flow model calibration and prediction. The fourth objective, to assess lateral movement of water from the spreading areas, cannot be fully addressed until flows in the Big Lost River require diversion of water to the spreading areas. However, the data acquired by the advanced tensiometers will establish baseline conditions for later comparisons when water is diverted to the spreading areas.

The focus of this report addresses the first objective, to provide field data that augment, confirm, or change the conceptual model for water transport in the unsaturated zone beneath the RWMC. The advanced tensiometer network provides in situ, continuous, water potential data that give a large-scale picture of the deep moisture system at the RWMC. These data will be evaluated in the context of assessing the conceptual flow model in the vadose zone by characterizing the temporal and spatial water potential trends, moisture distribution, and deep percolation in the subsurface to 73.5 m. A general conceptual model of flow is described in Section 1.1, to provide a framework for the data evaluations presented in this report.

1.1 Hydrological Conceptual Model

The conceptual flow model in the vadose zone at the RWMC proposes long periods of stable moisture contents that do not change significantly over time, resulting in unit gradients and constant flux rates at depth. A unit gradient exists when there is little-to-no change in water potential with respect to depth or elevation, resulting in a hydraulic gradient of one. Under a unit gradient, flow is driven by gravity rather than by large differences in water potentials.

These periods of stability are occasionally interrupted by episodic recharge events. Major sources of water at the surface are direct precipitation and run-off from snowmelt, which concentrates standing water in topographically low areas. Rapid snowmelt, combined with rain, caused flooding in pits and trenches within the SDA in 1962, 1969, and 1982 (Barraclough et al. 1976; Bargelt et al. 1992). Local run-off from late winter and early spring snowmelt has the greatest potential for extensive infiltration because these events occur when evapotranspiration rates are low.

In general, infiltration within the SDA is thought to be higher than outside the SDA. McElroy (1990) found higher (comparatively wetter) matric potentials in surficial sediments within the SDA compared to surficial sediments outside the SDA. Cecil et al. (1992) estimated recharge rates of 0.36 to 1.1 cm/year outside the SDA, at a site located near the northern boundary of the SDA. In contrast, McElroy (1993) and Bishop (1995) estimated recharge that ranged from 0.1 to 49.4 cm/yr during spring recharge from snowmelt inside the SDA. Laney et al. (1988), McElroy (1990), and Bishop (1998) suggest infiltration at the surface is highly nonuniform and is concentrated in surface depressions such as drainage ditches or in pits or trenches that flooded in the past.

During localized recharge events, wetting fronts move through the surficial sediments and into the underlying basalts. Downward movement through the basalts is assumed to occur primarily through open or sediment-filled fractures or joints, rather than the basalt matrix (Holdren et al. 2002). Hubbell et al. (2002) monitored the advance of a wetting front in the SDA that moved through basalt to the 12-m depth at a rate of 0.1 m/day. With a larger water source, such as during the Large-Scale Infiltration Test performed near the RWMC (Wood and Norrel 1996), the advance of the wetting front through the basalt to the first sedimentary interbed was on the order of 5 m/day.

It is assumed the downward pulse of the wetting front is eventually slowed as the moisture is stored in sediments or diverted laterally by geologic media with contrasting hydraulic conductivities, such as dense unfractured basalt layers or sedimentary interbeds. Two major sedimentary interbeds are located at approximately 34 m (the BC sedimentary interbed) and 73 m (the CD sedimentary interbed). In the Large-Scale Infiltration Test (Dunnivant et al.1998) water movement was predominantly vertical through fractured basalt to the BC interbed at a depth of 55 m, but perching and lateral movement was reported above the BC sedimentary interbed.

Additional sources of water to the subsurface beneath the SDA may be derived through lateral underflow from the Big Lost River and spreading areas (Figure 1). Rightmire and Lewis (1987) and Hubbell (1990) present evidence that suggests the spreading areas are a source for perched water located in basalt above the CD interbed. Through the use of a tracer, Nimmo et al. (2002) confirmed the presence of water from the spreading areas in perched water above the CD interbed beneath the SDA. The investigators hypothesize that water from the spreading areas moves primarily downward, but a portion is diverted laterally by low hydraulic conductivity layers.

1.2 Scope

In this report, water potential data will be evaluated to help assess assumptions in the conceptual flow model. The data analyses will:

- Determine if water potentials are stable or have changed over time

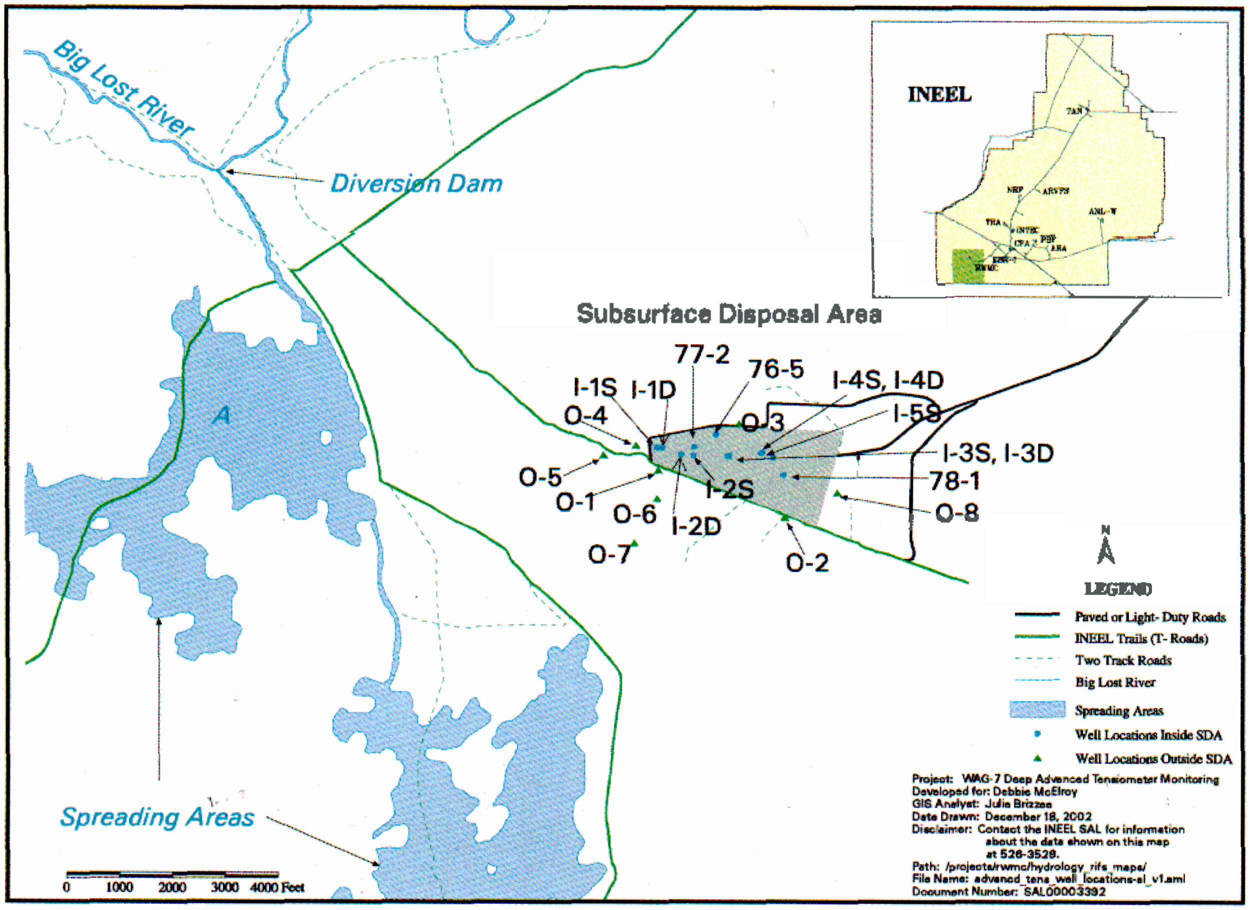

Figure 1. Location of Subsurface Disposal Area (SDA) relative to the Idaho National Engineering and Environmental Laboratory, the Big Lost River, and the spreading areas. Advanced tensiometer borehole locations are shown. I-series wells are located inside the SDA, and O-series wells are located outside the SDA.

- Evaluate spatial distribution of water potentials to determine the effects of focused surface infiltration through drainage ditches or flooding of pits and trenches beneath the SDA

- Determine if the instrumented depths are under an overall unit gradient, implying drainage by gravity

- Estimate deep percolation rates using the unit gradient method, if applicable.

1.3 Document Overview

Section 2, which follows, describes the advanced tensiometers, describes installation of the advanced tensiometers in boreholes at the RWMC, and presents borehole locations. Water potential data from tensiometer monitoring through August 2002 are presented and discussed in Section 3. Water potentials over time are used to determine steady state or, alternatively, transient moisture conditions. Spatial comparisons of water potentials are performed to determine the effects, at depth, of facilitated infiltration in the SDA. Deep percolation rates at monitored locations in the sedimentary interbeds are then estimated. Section 4 summarizes results and makes recommendations for future work.

2. ADVANCED TENSIOMETER INSTALLATION AND DATA COLLECTION

Advanced tensiometers are instruments that yield water potential data at any depth. Water potential is a means of measuring the relative energy state of water to evaluate the status and movement of water. Under fully saturated conditions, water is at hydrostatic pressures greater than atmospheric pressure, and water potential can be considered positive. Under unsaturated conditions, capillary and adsorptive forces hold water in the porous medium. In this unsaturated state, water potential is considered to be negative, by convention, because the hydrostatic pressures are less than atmospheric pressures. The advanced tensiometer measurements are expressed in terms of an equivalent head of water, such as the centimeters of water units used in this report.

When analyzing the temporal response of a single tensiometer, the medium can be considered homogeneous. In this case, the higher (or less negative) the water potential measurement, the greater the wetness of that medium. Increasing water potentials over time indicate wetting of the medium, and conversely, decreasing water potentials indicate drying of the medium over time. Positive water potentials indicate saturated conditions, while negative water potentials indicate unsaturated conditions. Care must be taken when comparing multiple tensiometers at different locations at any single time in an effort to determine moisture distribution. Soil type greatly affects the relative moisture content at a single water potential value.

The advanced tensiometer consists of a porous cup installed at a specified depth with an attached polyvinyl chloride (PVC) pipe that extends to land surface (Figure 2). A volume of water is placed in the PVC pipe to fill the porous cup. A pressure transducer is placed inside the PVC pipe and seated just above the porous cup by means of a rubber stopper, sealing the water chamber in the porous cup from the water in the PVC pipe. The water in the porous cup will move into or out of the formation until the partial vacuum in the cup is equal to the subatmospheric water pressure in the surrounding soil. The pressure transducer measurement of this partial vacuum is then considered equivalent to the soil water potential. A data logger, connected to the pressure transducer, continuously monitors and stores the data for subsequent analysis.

Over time, the subatmospheric conditions in the porous cup can remove air from the water reservoir. This entrapped air eventually lowers the water level in the water reservoir and induces a rise in water potential measurements of up to 12 to 15 cm of water (depending on the tensiometer model). A buildup of entrapped air or very dry conditions may also induce a total loss of water from the porous cup, resulting in a slow rise of water potentials to atmospheric pressures. Equilibration of water potentials after water is added generally occurs over a period of hours.

2.1 Advanced Tensiometer Installation

Figure 1 shows the locations of the wells containing the tensiometers. Tensiometer depths and adjacent lithology are listed in Table 1. Seventeen of the wells were installed and instrumented as part of the WAG 7 OU 7-13/14 hydrologic characterization activities (Settle and Dooley 2002). Wells with names beginning with an I (for inside the SDA) and with an O (for outside the SDA) were drilled and instrumented in Fiscal Year 2000.

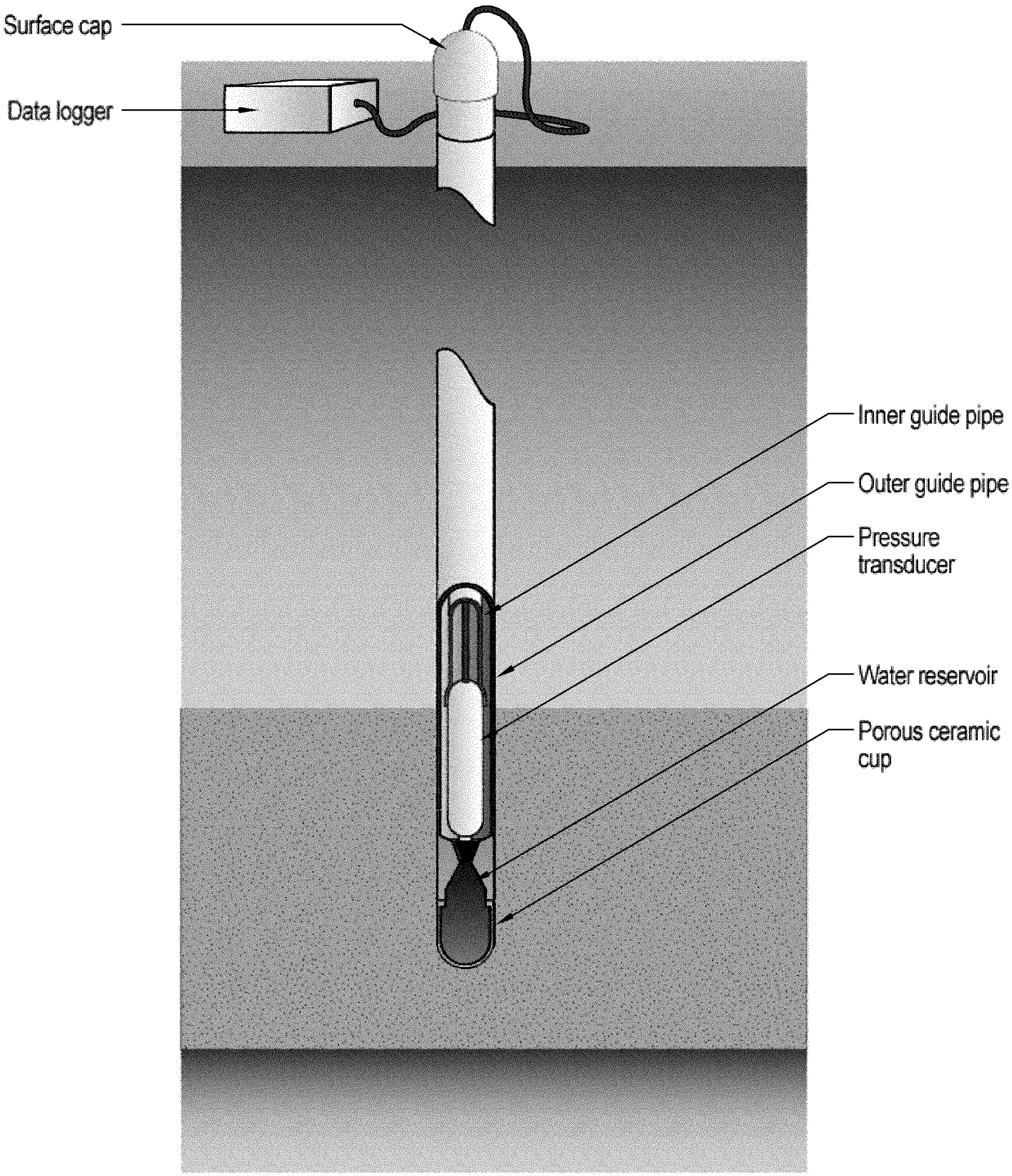

Figure 2. Schematic of advanced tensiometer, showing porous cup, transducer, and outer PVC guide pipe.

Table 1. Well names, instrument depths below land surface (bls), lithology adjacent to each instrument, and average water potentials and standard deviations based on measurements from February 2000 through August 22, 2002 (after equilibration).

Well	Tensiometer Depth[a] m (ft) bls	Lithology at Depth of Tensiometer	Average Water Potential (cm water)	Standard Deviation (cm water)
I-1S	31.4 (103)	BC sedimentary interbed	-30	±3
I-1D	69.2 (227)	CD sedimentary interbed	-320	±19
I-2S	28.7 (94)	Unknown, no recovery and no gamma log	-106	±11
I-2D	53.6 (176)	Basalt, massive	-72	±4
I-2D	68.0 (223)	CD sedimentary interbed	-241	±5
I-3S	28.3 (93)	BC sedimentary interbed	-39	±8
I-3D	69.8 (229)	CD sedimentary interbed	-187	±12
I-4S	29.7 (97.5)	Basalt/BC sedimentary interbed, near contact	-87	±7
I-4D	69.2 (227)	CD sedimentary interbed	-199	±8
I-5S	30.4 (99.7)	Basalt/BC sedimentary interbed, near contact	-124	±14
O-1	29.6 (97)	BC sedimentary interbed, no recovery	-180	±9
O-2	32.6 (107)	Basalt/BC sedimentary interbed, near contact	-131	±7
O-3	26.8 (88)	Basalt	-249	±11
O-3	67.4 (221)	Basalt/CD sedimentary interbed	-109	±8
O-4	33.5 (110)	BC sedimentary interbed	-154	±18
O-4	69 (226.5)	CD sedimentary interbed	-360	±27
O-5	32 (105)	Basalt/BC sedimentary interbed [b]	-144	±8
O-7	36.9 (121)	BC sedimentary interbed, no recovery	-195	±2
O-7	73.5 (241)	Basalt, rubbly	-27	±5
76-5	6.7 (22)	Sediment-filled fractures	-160	±67
76-5	9.4 (31)	AB sedimentary interbed[c]	-218	±23
76-5	11.6 (38)	Rubble zone	-140	±11
76-5	17.3 (57)	Horizontal fracture with sediment	-67	±8
76-5	24.4 (80)	Sediment-filled fractures	-111	±6
76-5	29.6 (97)	Moist basalt	-85	±13
76-5	31.4 (103)	BC sedimentary interbed	-161	±3
77-2	10.0 (32.8)	AB sedimentary interbed[c], reddish-baked silt	-244	±21
77-2	17.1 (56)	Basalt	-121	±5
77-2	27.4 (90)	Basalt	-94	±9
78-1	10.7 (35)	Fractured basalt, with sediment infilling	-351	±18

a. Tensiometers at O1-229, O2-241, O8-229, O6-227 (in bentonite) and 78-1(25.6 m) (not operational) are excluded from this listing.

b. Discrepancy between geologists log and gamma log for O-5. Used natural gamma log placement of interbed at 32.2 m.

c. Sedimentary interbed, not continuous, located approximately 8.4 m below land surface.

The three remaining wells (76-5, 77-2, and 78-1) were drilled and instrumented under other programs. Well 76-5 was cored in 1976 (Humphrey and Tingey 1978) as part of a radionuclide migration study. The lower portion of 76-5 was cemented to 34 m below land surface (bls) and used as an observation well for perched water (Hubbell et al. 2002). A nested series of advanced tensiometers were installed in this open interval in June 1996. Similarly, wells 77-2 and 78-1 were drilled in 1977 and 1978 respectively, and remained open until they were instrumented with advanced tensiometers in December 1995. Portable tensiometers, in tandem with removable suction lysimeters, were placed at the bottom of wells 78-1 and 77-2 in December 1999.

Tensiometers in the I- and O-series wells were installed with a silica flour/silica sand slurry around the porous cup to obtain a hydraulic connection between the cup and the geologic formation (Settle and Dooley 2002). Granular bentonite was used to seal the remainder of the borehole between the instrumented depths. The BC and CD sedimentary interbeds (at approximately 34 and 73 m) were generally targeted for tensiometer placement, although some instruments were placed adjacent to basalt.

Installation methods for tensiometers in wells 76-5, 77-2, and 78-1 differed from the methods used for the I- and O- wells. At 76-5, the porous cups of the tensiometers were placed in a 0.3-to-one-meter layer of silt loam to hydraulically connect the porous cup to the fractured basalt (Hubbell et al. 2002). Granular bentonite (about 0.3 m) layers were placed above and beneath the loam-filled monitoring depths to isolate the monitoring intervals. Coarse sand (2.4 to 3.3 mm) filled the remaining portions of the borehole between the tensiometer monitoring depths with thin layers of bentonite placed about every 2 m to inhibit moisture flow through the borehole. Tensiometers in wells 77-2 and 78-1 were placed in dry native fill (loam), and bentonite layers were placed between instrumented depths to isolate each instrumented depth. Well-construction diagrams for 77-2 and 78-1 are included in Appendix A.

2.2 Data Collection and Tensiometer Maintenance

Pressure transducers (measurement range of -800 to +800 cm of water, Electronic Engineering Innovations, Las Cruces, New Mexico) were placed in the tensiometers and connected to either models 510X, 10X, and 23X Campbell data loggers (Campbell Scientific, Inc., Logan, Utah) or Tumut Gadara data loggers (Electronic Engineering Innovations, Inc., Las Cruces, New Mexico). This system collects continuous water potential measurements at each instrumented depth. Data were collected at least every four hours and data loggers were generally downloaded on a monthly basis. The pressure transducers were calibrated prior to installation.

Maintenance of the advanced tensiometers required the periodic addition of water to the porous cup. Some tensiometers required additional water after four months of operation, others operated over two years without the addition of water. Transducers were replaced as needed when water potentials became erratic.

3. RESULTS AND DISCUSSION

Water potential data over time for each borehole are presented in Figures 3 through 6, from the start of monitoring through August 2002. The long-term water potentials (which excludes short-term events such as episodic infiltration) at tensiometer locations inside and outside the SDA ranged from a near-saturated -30 cm of water in the BC sedimentary interbed at I1S to a -400 cm of water in the CD sedimentary interbed at O4. Monitoring began at the majority of the wells (I- and O-series wells) in spring 2000, and approximately 2-1/2 years of data are presented from those wells. In contrast, approximately 6 years of data are presented from advanced tensiometers in three wells, 76-5, 77-2, and 78-1, beginning in 1996. For the following discussions, tensiometers are identified by well number and the depth (in meters, rounded off), such as I1S-31 for the tensiometer at the 31.4 m depth in I-1S.

Advanced tensiometer data can be affected by changes in infiltration and drainage. An increase in infiltration, or wetting of the medium, will cause an increase in water potentials. An increase in drainage, or drying of the medium, will cause a corresponding decrease in water potentials.

In addition to infiltration and drainage, advanced tensiometer data can be affected by initial equilibration of the backfill to the moisture of the surrounding bulk matrix. Equilibration of the backfill material occurred before the start of transducer measurements at most tensiometer locations, as evidenced by the initially stable water potentials. These transducer measurements were initiated one to 12 months after well construction. However, three wells did track equilibration of the backfill. The dry silt loam backfill in 76-5 (Figure 6a) equilibrated within two months (Hubbell et al. 2002) as shown by the initial rise of water potentials in June 1996, when the tensiometers and transducers were installed, to more stable values. In I5S-30, the drying of the backfill occurred within a two-month period. At O5-32, water potentials indicate the majority of the equilibration occurred over a ten-month period and possibly continued another eight months (until July 2001).

Changes in barometric pressure and air entry into the tensiometer cup also affect water potential data. The cyclic rise and decline in water potentials that are most prominent in I1D-69, I3S-28, and I5S-30 are the result of barometric fluctuations. These short-term cycles do not represent infiltration events. Abrupt 10 to 15 cm declines in water potentials, such as observed in September 2002 at O2-33, were the result of the addition of water to the tensiometer cup. When entrapped air builds up in the porous cup, water potentials will show an artificial rise that is corrected by adding water to the tensiometer cup.

Soil-water sampling from nearby lysimeters also affected these water potential data. Lysimeters were generally placed within one meter of the tensiometers in the same silica flour interval. The timing of the vacuums applied to nearby lysimeters (see Figure 3c, I2S-29, for example) corresponds directly with the observed steep drops in water potential measurements. These steep drops were sometimes followed by smaller upward spikes. These upward spikes corresponded in time with the release of vacuum and application of positive pressures to the nearby lysimeters to bring the soil-water sample up to the surface. The effects of the lysimeter sampling on the water potentials near the tensiometer dissipate within two to four days.

Data gaps in water potential profiles (Figure 3d, I2D-68, during spring 2001, for example) were due to equipment malfunctions (such as low batteries or transducer failure) or loss of water from the tensiometer cup.

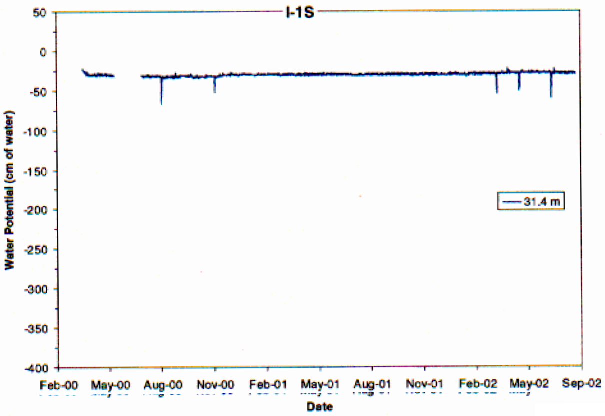

Figure 3a. I-1S.

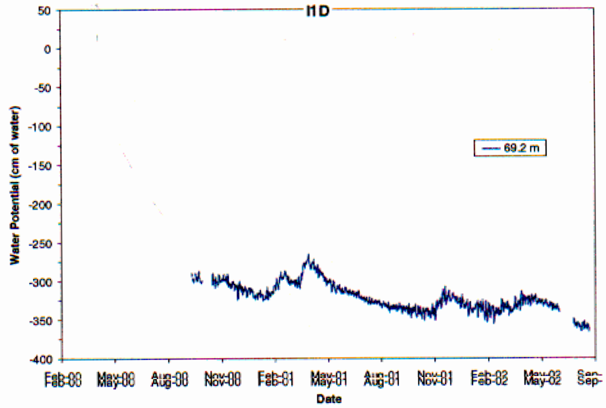

Figure 3b. I-1D.

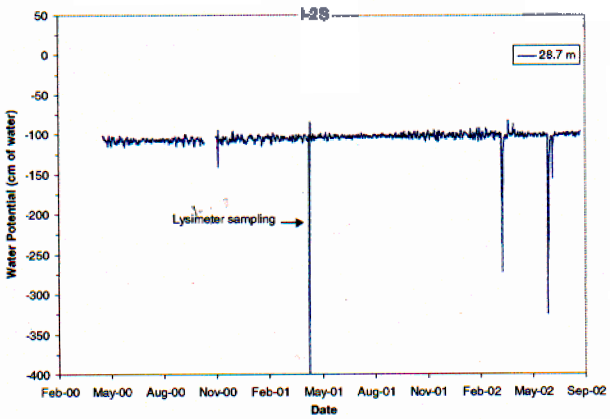

Figure 3c. I-2S.

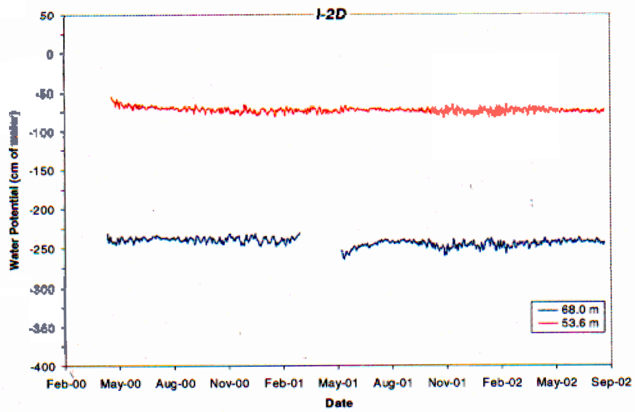

Figure 3d. I-2D.

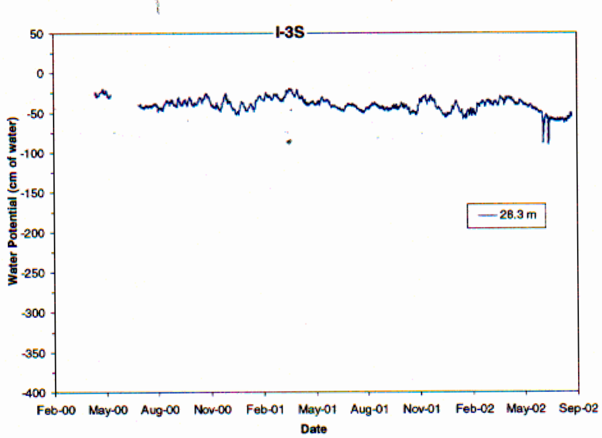

Figure 3e. I-3S.

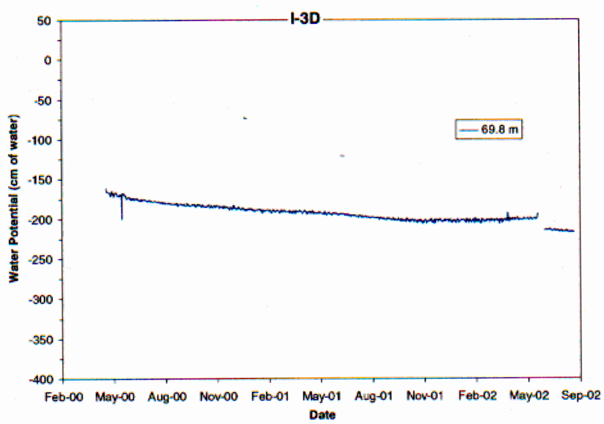

Figure 3f. I-3D.

Figure 3. Water potentials over time at (a) I-1S, (b) I-1D, (c) I-2S, (d) I-2D, (e) I-3S, and (f) I-3D.

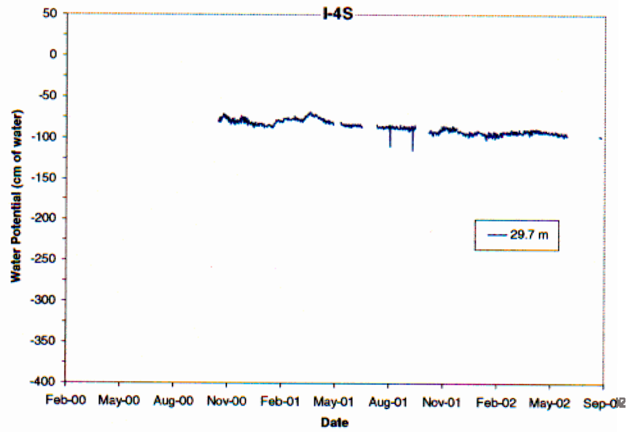

Figure 4a. I-4S.

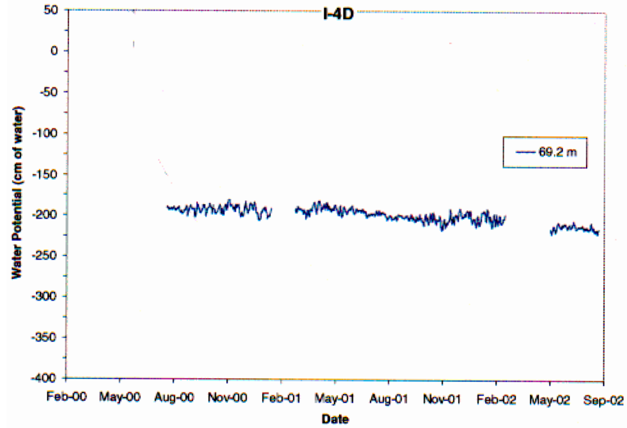

Figure 4b. I-4D.

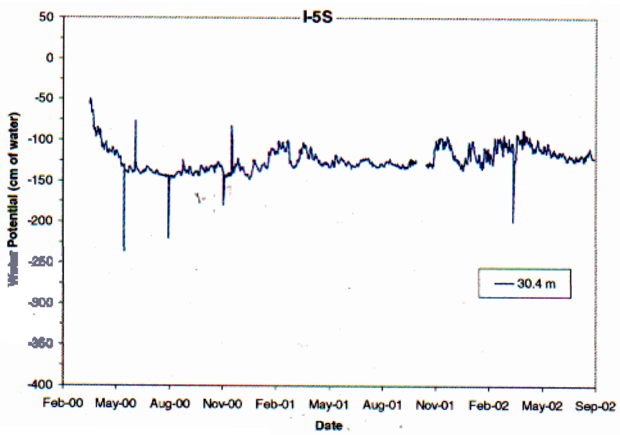

Figure 4c. I-5S.

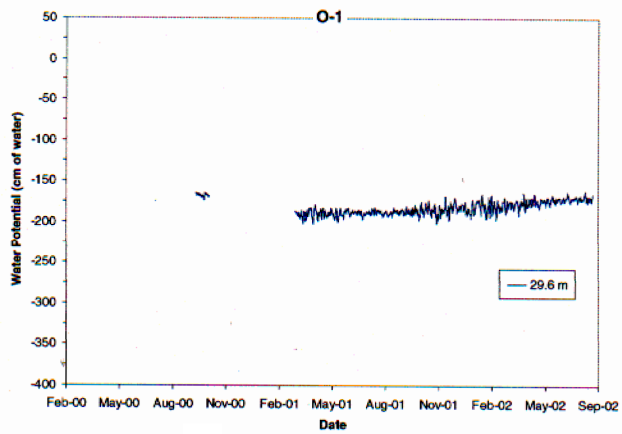

Figure 4d. O-1.

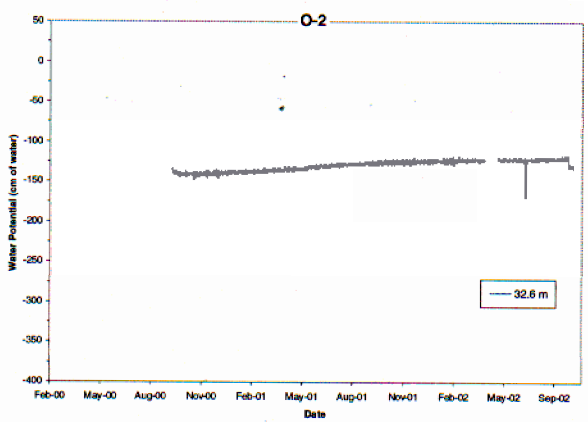

Figure 4e. O-2.

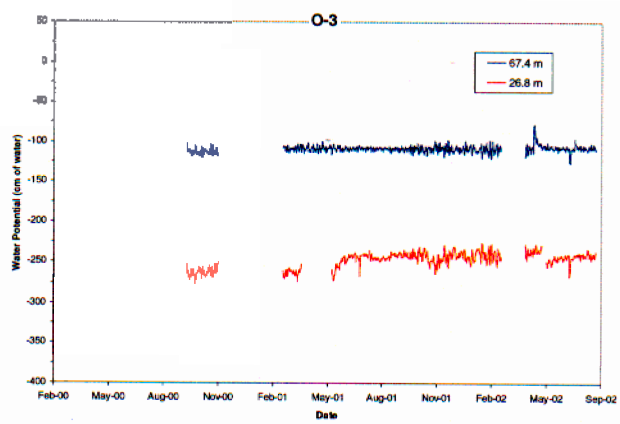

Figure 4f. O-3.

Figure 4. Water potentials over time at (a) I-4S, (b) I-4D, (c) I-5S, (d) O-1, (e) O-2, and (f) O-3.

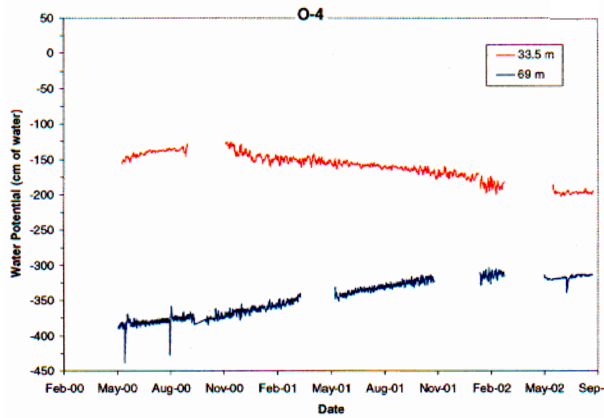

Figure 5a. O-4.

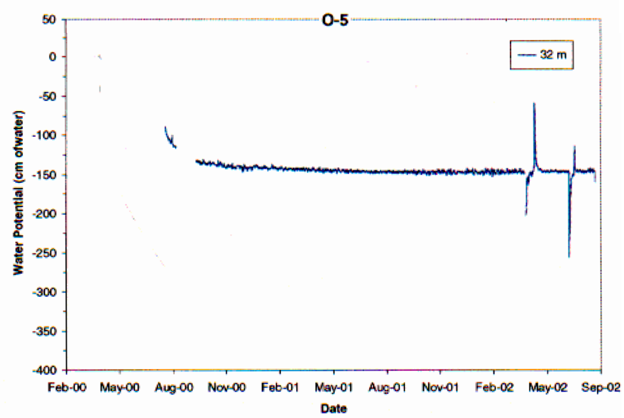

Figure 5b. O-5.

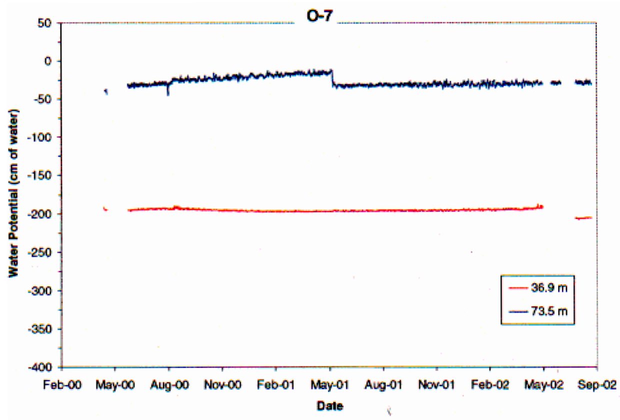

Figure 5c. O-7.

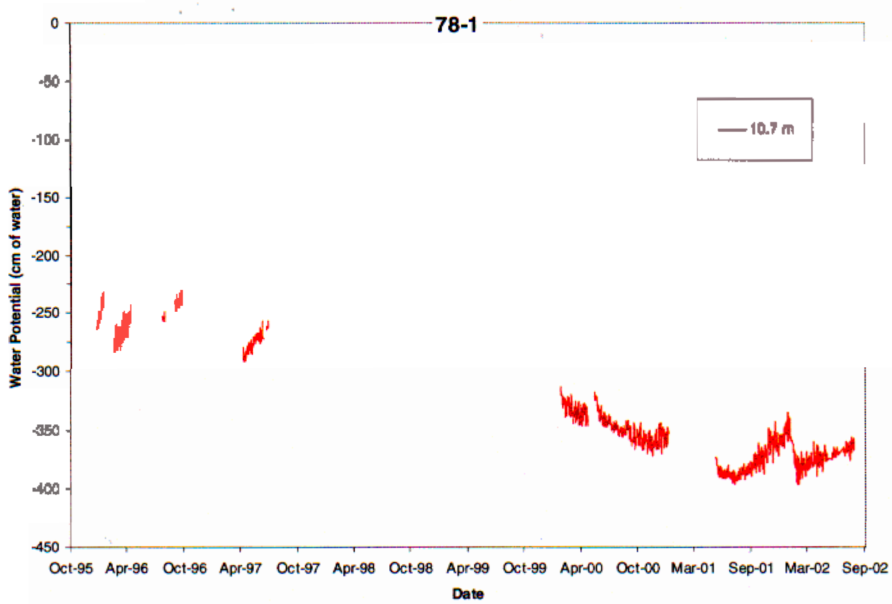

Figure 5d. 78-1.

Figure 5. Water potentials over time at (a) O-4, (b) O-5, (c) O-7, (d) 78-1.

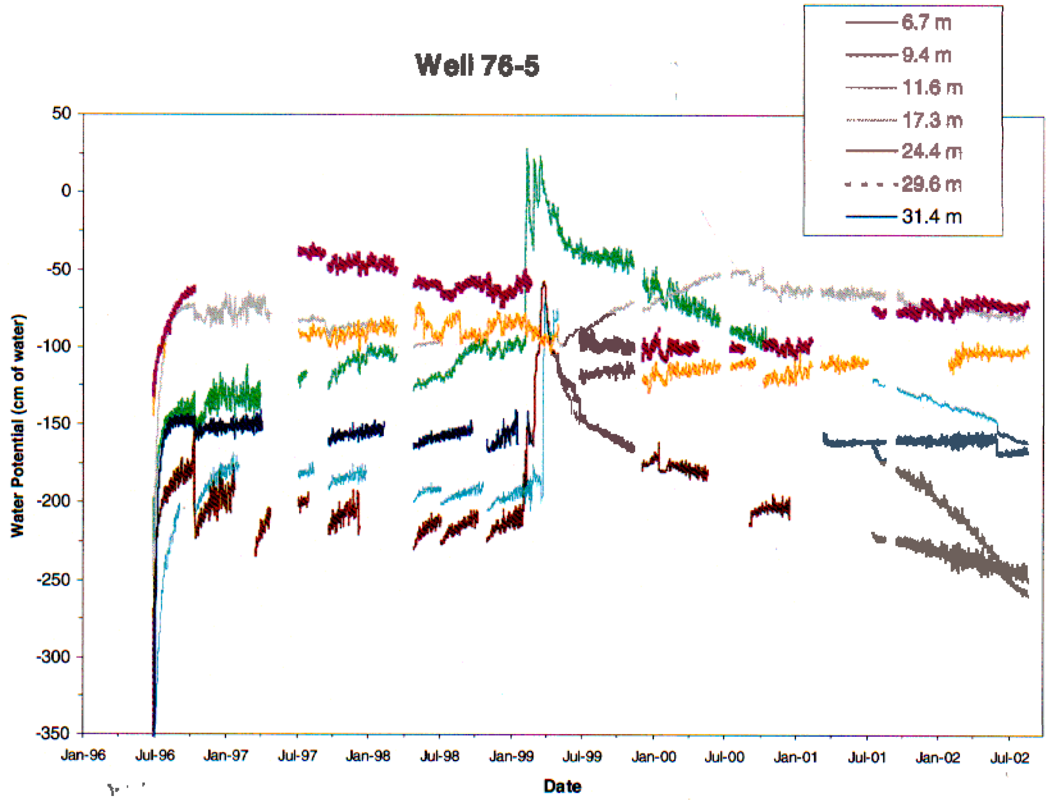

Figure 6a. 76-5.

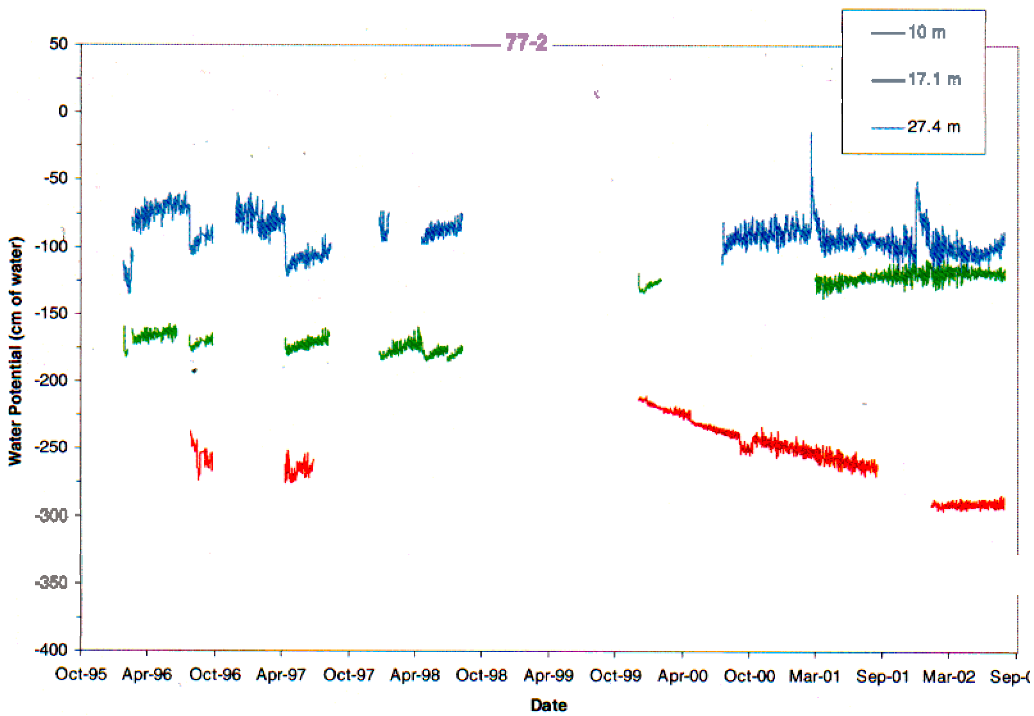

Figure 6b. 77-2.

Figure 6. Water potentials over time at (a) 76-5 and (b) 77-2.

3.1 Water Potential Temporal Trends

Water potentials that do not change over time suggest steady-state conditions. Steady state implies either a constant water flux or hydrostatic conditions. Steady state is relative to the monitored period; long-term changes in water potentials may not be large enough to discern over a 2-year period. These long-term changes will become more evident as the monitoring period is extended. Transient conditions imply changes in moisture over time, presumably from changes in infiltration at land surface. Water potentials at monitored locations from spring 2000 through August 2002 were evaluated for temporal trends. Two locations (I-5S and O-1) were indeterminate and were not included in this characterization. Locations that exhibited stable water potentials are discussed in Section 3.1.1, and locations characterized by transient water potentials are discussed in Section 3.1.2.

3.1.1 Steady State Moisture Conditions

Stable water potentials indicate steady state or near-steady state moisture conditions. Tensiometer locations that exhibited stable water potentials since spring 2000 were all at depths of 17 m or greater. Fifteen of the 23 tensiometers (excluding I-5S and O-1 as indeterminate) located at depths of 17 m or greater exhibited stable water potentials. Water potentials were stable in basalt at 772-17, 772-27, 765-24, 765-30, I2D-54, O3-27, and O7-74. Although water potentials at 765-24 and 765-30 are offset from the main data in the July 1999 and August 2001 time period, these offsets are the result of improperly functioning transducers and do not represent drainage and infiltration in the basalt. Two data spikes do occur in 772-27, in March 2001 and December 2002, but these spikes appear to be artificially induced. This depth (772-27) is monitored by a portable tensiometer in an open standpipe, and condensation in the open borehole may be collecting and trickling down the sides of the well, causing a temporary rise in water potentials that dissipates quickly. In the BC sedimentary interbed, water potentials were stable at 765-31, I1S-31, I2S-29, O2-33, O5-32, and O7-37. In the CD sedimentary interbed, water potentials were stable at I2D-68 and O3-67. The locations of the wells that exhibited stable water potentials are highlighted with blue circles in Figure 7. The steady-state conditions exhibited at the deep locations are consistent with the assumption in the conceptual model of long periods of stable water potentials that do not change significantly over time.

Those locations exhibiting stable water potentials were located both inside and outside the SDA. Steady-state conditions were observed at the majority (seven out of nine) of the tensiometer locations outside the SDA, with O4-34 and O4-69 being the only exceptions. The steady-state locations inside the SDA were generally farther from the main east-west main road and associated drainage ditches, such as I-2D, I-2S, 77-2, and 76-5.

Two well locations, 76-5 and 77-2, provided advanced tensiometer measurements prior to the August 2002 time period. Little change in water potentials was observed at depths below 17 m to the BC sedimentary interbed at 76-5 and directly above the BC sedimentary interbed at 77-2, during the wetter years of 1997 and 1998 (26.6 and 25.7 cm annual precipitation, respectively) and during periods of flow diversion into the spreading areas. These locations in and above the BC sedimentary interbed do not appear to have been affected by the lateral flow from the spreading areas in 1997 and 1998.

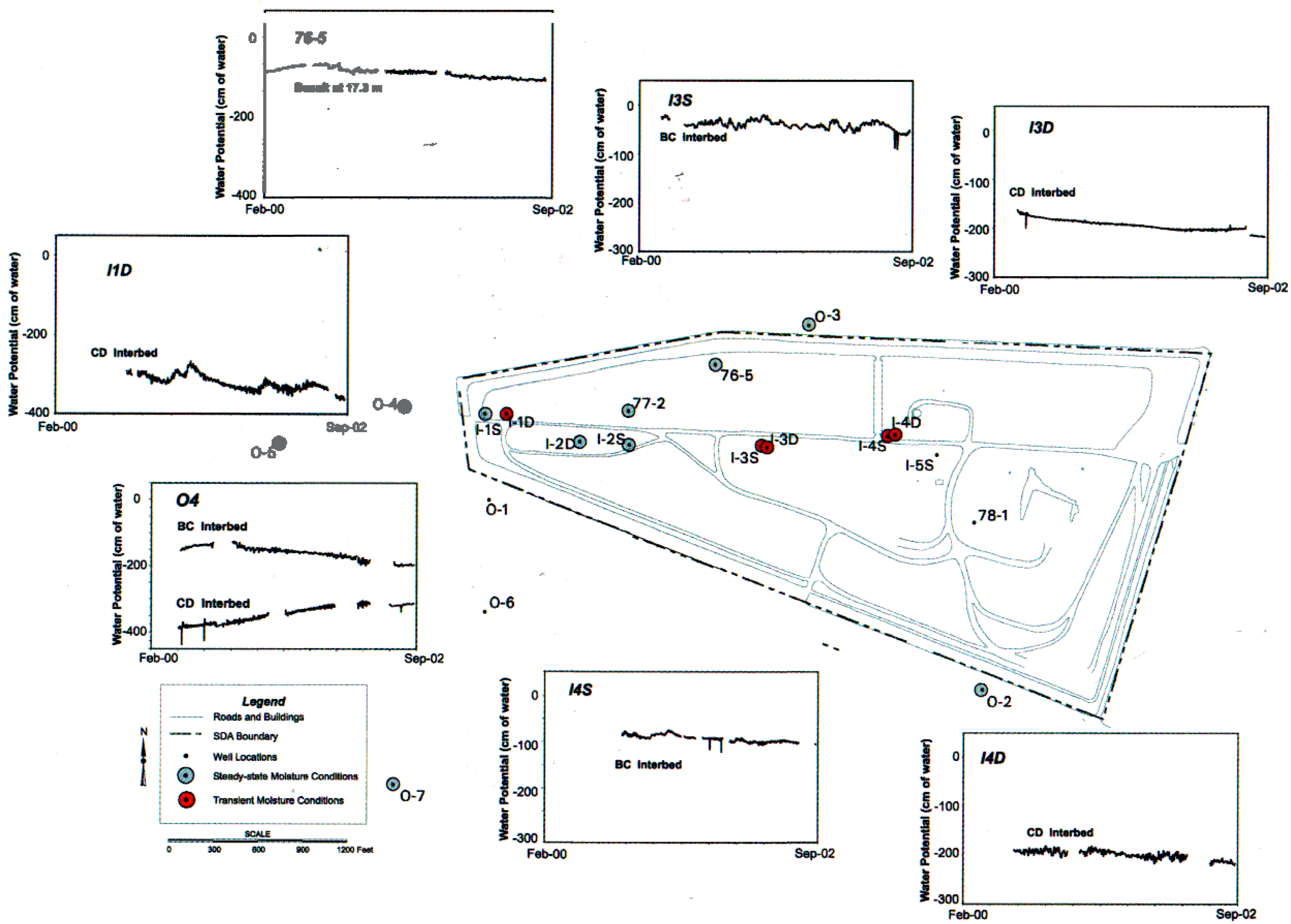

Figure 7. Locations of wells with tensiometers at or below the 17-m depth. Blue highlighted circles indicate steady-state conditions and open circles indicate transient moisture conditions. Well locations with transient conditions tend to be located near the main east-west road through the Subsurface Disposal Area.

3.1.2 Transient Moisture Conditions

Water potentials did change over time at 13 advanced tensiometer locations. Specific recharge events over short time periods, such as from snowmelt and run-off, are generally easy to identify because of the large changes in water potentials. Small changes in water potentials over long timeframes are more difficult to identify. These long-term transient trends are defined in this report by the presence of a long-term shift in water potentials of more than 15 cm of water, during the period from January 2000 through August 2002. The following sections discuss the long-term drying trends observed at several tensiometer locations (Section 3.1.2.1) and the long-term wetting trend detected at one tensiometer location (Section 3.1.2.2). Although no episodic recharge events occurred over the spring 2000 through August 2002 time period, the episodic recharge that occurred in 1999 is discussed in Section 3.1.2.3.

3.1.2.1 Long-Term Drying. Long-term drying trends were observed in the shallower basalts and sediments, as well as in the BC and CD interbeds. The most pronounced drying and greatest decrease in water potentials occurred in the shallower basalts and interbed sediments at or above the 12-m depth at 772-10, 781-11, and 765-7, 765-9, and 765-12. Most of these shallower locations exhibited water potentials that were currently lower than the pre-1999 values. A gradient reversal indicated flow direction changed from downward drainage to upward capillary flow in August 2002 between the 6.7- and 9.4-m depths in 76-5. Low precipitation over the last few years may have been a factor in the decreased water potentials at the shallower (less than 12-m) depths. Figure 8 shows the annual precipitation (October through September) since 1991 at the Central Facilities Area at the Idaho National Engineering and Environmental Laboratory (INEEL) (NOAA 2002). Annual precipitation has decreased to less than 14 cm for the past three years (2000, 2001, and 2002), which is less than the average annual precipitation for this area of approximately 22 cm per year (Clawson et al. 1989). The shallower (12 m or less) sediments and basalts may be responding to decreased surface infiltration.

In the deeper basalts and sediments, water potentials gradually decreased in the basalt at 765-17, in BC interbed sediments at I3S-29, I4S-30, and O4-34, and in the CD interbed sediments at I1D-69, I3D-70, and I4D-69. The well locations at which these deeper drying trends occur are shown in Figure 7, with red circles, for comparison with steady-state locations (blue circles). These wells that reflect drying trends are, with the exception of 76-5, located along the main road that runs through the SDA and were sited to increase the chances of encountering perched water, for sampling purposes. The main road is bordered on both sides by ditches that run the length of the road through the SDA. These ditches collect drainage from surrounding areas, and tend to focus run-off and infiltration along the road. Areas proximal to the main road and drainage ditches receive more extensive surface infiltration during years of higher precipitation and run-off (Bishop 1998). Sedimentary interbeds beneath those areas of focused infiltration may be responding to decreased run-off from three years of low precipitation.

3.1.2.2 Long-Term Wetting. One tensiometer, O4-69 in the CD interbed (Figure 5a), showed a gradual rise in water potentials of 75 cm of water from at least May 2000, when monitoring began, to March 2002. The increase in water potentials occurred over the same timeframe as the drying of sediments in the BC interbed at the same location, O4-34. The calibration of the transducer was checked and it was operating properly. Possible causes for the rise in moisture include downward drainage from overlying basalt or the BC sedimentary interbed, or delayed inflow from the spreading areas, approximately 1.6 km west of O4. This well was sited to evaluate the influence of the spreading areas on moisture in the subsurface; however, the last release of water to the spreading areas was in June 1999. Monitoring is needed during and after periods of inflow to the spreading areas to determine if moisture changes in these tensiometers are related to inflow from the spreading areas. Additionally, if monitoring indicates water potentials in both the BC and CD interbed sediments in O-4 level off in a delayed fashion (with the BC interbed sediments leveling off before the CD interbed sediments), it is likely that drainage from the BC interbed and infiltration into the CD interbed are related.

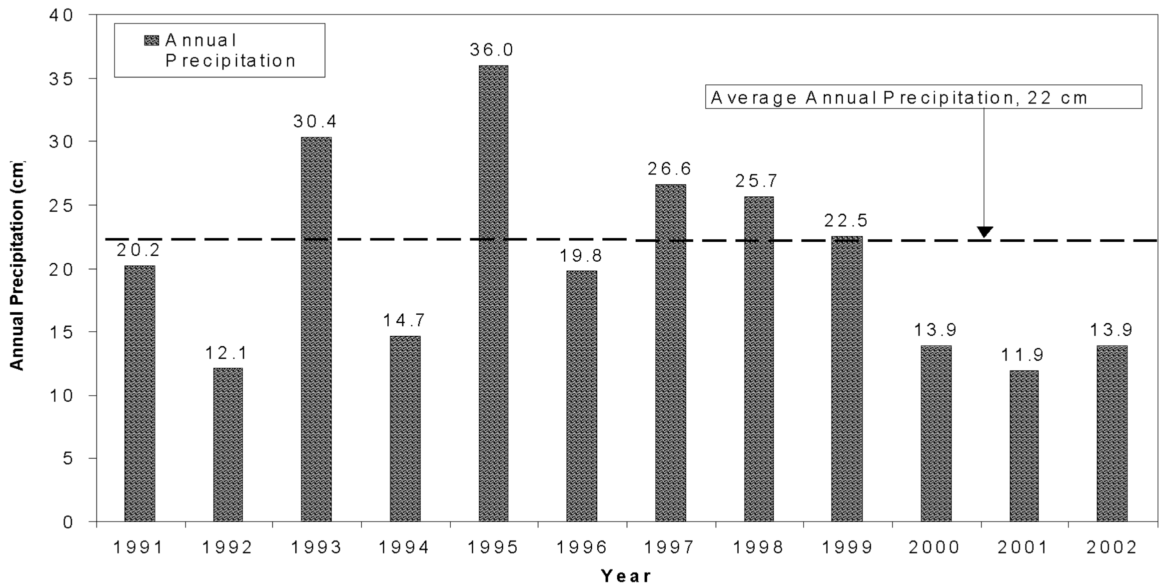

Figure 8. Precipitation at the nearby Central Facilities Area (approximately 8 km northeast of the Radioactive Waste Management Complex for each water year (October through September) since 1993. The historical average annual precipitation is 22 cm (Clawson et al. 1989).

3.1.2.3 Episodic Infiltration. No episodic recharge events were recorded at these monitoring locations over the spring 2000 through August 2002 time period. However, an earlier recharge event was recorded at 76-5 in 1999 following the spring thaw (Hubbell et al. 2002 and McElroy and Hubbell 2001). The infiltration event was attributed to the local topographic low area around 76-5, which allowed water from surrounding areas to drain to and collect at 76-5 over frozen ground until the ground thawed and infiltration occurred. Figure 6a shows a rapid increase in water potential at the 6.7-, 9.4-, and 11.6-m depths in February and March of 1999, followed by a gradual rise in water potential at the 17.3-m depth in June 1999. The wetting front moved quickly through the basalt, from 6.7 to 11.6 m in 43 days, with an average advance of 0.1 m/day. Water potentials at the 17.3-m depth indicated a slowing and dampening of this wetting front, which moved from 11.6 to 17.3 m over a 5-month period. Sediments and rubble at 11.6 m may have slowed the downward movement of the wetting front. Since the 1999 infiltration event, water potentials in basalts to the 9.4-m depth have consistently decreased, and current (August 2002) water potentials are less than pre-1999 values. Decreasing water potentials at 76-5 indicate overall drying is occurring to at least the 17.3-m depth. No long-term wetting or drying of the matrix was detected at the deeper monitored depths from 24.4 to 31.4 m bls.

Water potential data suggest a 1999 infiltration event also occurred at well 77-2 in the SDA (Figure 6b). The data did not fully capture the actual event, but water potentials at the 10-m depth increased approximately 50 cm of water from July 1997 to December 1999. After December 1999 the water potentials decreased to preinfiltration levels. A similar water potential increase may have occurred at the 17.1-m depth, but a corresponding drainage was not observed. The infiltration event does not appear to have extended to the 27.4-m depth. The short-term upward spikes in 2000 and 2001 appear to be artificially induced by the use of a portable tensiometer at 772-27 (Section 3.1.1).

3.1.3 Summary and Recommendations Relative to Temporal Trends

Steady-state conditions occurred at the majority of the deepest (17 m or deeper) advanced tensiometer locations, which is consistent with the long periods of stable moisture contents proposed in the conceptual flow model. These well locations were generally those wells farthest from the main east-west road and associated drainage ditches. However, long-term drying trends were also observed at or below 17m, at some advanced tensiometer locations nearest the main SDA road and ditches. It was hypothesized that sedimentary interbeds beneath areas of focused infiltration (such as near drainage ditches) may be responding to decreased run-off from the last three years (2000 through 2002) of low precipitation. Shallow sediments and basalts at depths above 12 m exhibited the most pronounced drying, and were likely responding to lower-than-average precipitation over the last three years. A long-term wetting trend was detected at 04-69, but the cause could not be determined.

No episodic recharge events were recorded at 76-5 and 77-2 over the spring 2000 through August 2002 time period. Episodic recharge was detected to the 17.3-m depth at 76-5 (McElroy and Hubbell 2001; Hubbell et al. 2002), and to the 10-m depth at 77-2 in 1999 following the spring thaw. The 76-5 infiltration event was attributed to a local topographic low area surrounding 76-5 which allowed standing water to collect at the well.

Monitoring at most of the tensiometer locations (I- and O-series wells) was initiated in late spring 2000. This coincided with a decrease in precipitation from a near-normal annual precipitation of 22 cm in 1999 to less than 14 cm per year in 2000, 2001, and 2002 (Figure 8). Additionally, the last release of water to the spreading areas, west and south of the SDA, was in June 1999. Advanced tensiometers in the I- and O-series wells were installed to determine the effects of increased infiltration at the surface and to determine the effects of lateral flow from the spreading areas to the SDA. Monitoring should be extended to collect data during normal and above-normal precipitation years, as well as during periods when water is discharged to the spreading areas.

3.2 Spatial Comparison of Water Potentials

Water potentials were compared laterally and vertically between monitored locations. To perform the spatial comparisons, it was necessary to assume the BC and CD sedimentary interbeds were each homogeneous mediums. Well logs (Settle and Dooley, 2002) indicate the sedimentary interbeds are heterogeneous, but that sand-sized materials dominate the BC interbed and silt-sized materials dominate the CD interbed. To simplify these spatial analyses, it was assumed the BC sedimentary interbed was a homogeneous sand unit and the CD interbed was a homogeneous silt unit. In Section 3.2.1, water potentials inside the SDA are compared to water potentials outside the SDA, for both the BC and CD sedimentary interbeds. In Section 3.2.2, water potentials in the BC sedimentary interbed are compared to those in the CD sedimentary interbed. Finally, in Section 3.2.3, water potentials in basalt are evaluated with depth.

To simplify the spatial comparisons, average water potentials were calculated for each advanced tensiometer location and are listed, with their standard deviations, in Table 1. Water potential measurements from February 2000 through August 22, 2002, were used to calculate the means and standard deviations. In Figure 9, the average water potentials are plotted by depth with separate symbols for the four lithologic groups: basalt, AB interbed sediments, BC interbed sediments, and CD interbed sediments.

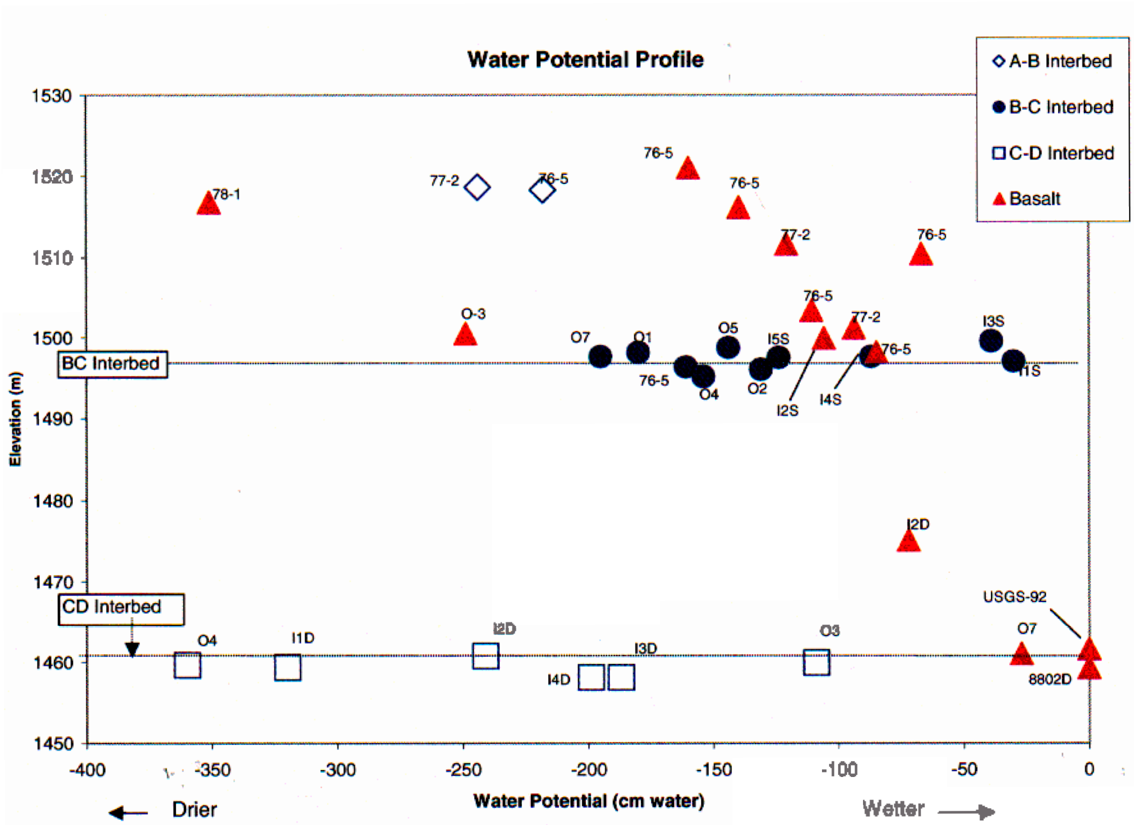

Figure 9. Average water potentials for tensiometer locations in the AB sedimentary interbed, BC sedimentary interbed, CD sedimentary interbed, and basalt, plotted by elevation. Some wells have multiple instruments and are plotted without attempting to distinguish between them (Well 76-5, for example).

3.2.1 Comparison of Water Potentials Inside the SDA to Outside the SDA

Water potential data in the BC interbed sediments suggest wetter conditions inside the Subsurface Disposal Area (SDA) than outside the SDA. In Figure 9, average water potentials in the BC interbed are shown with closed circles. The average water potentials at I-5S, I-4S, I-3S, and I-1S (inside the SDA), are higher than –125 cm of water, whereas average water potentials at O-7, O-1, O-2, and O-4, which are outside the SDA, are less than -125 cm of water. Assuming a homogeneous medium, higher (less negative) water potentials indicate higher moisture. Past studies (Laney et al. 1988 and McElroy 1990) concluded that there were wetter conditions inside the SDA than outside the SDA, based on data in the shallow surficial sediments. The deep tensiometer data suggests wetter conditions inside the SDA extend to the depth of the BC interbed, approximately 34 m bls. Inside the SDA, low-lying areas such as drainage ditches or open pits or trenches, collect run-off from snowmelt and high intensity rains. Focusing of flow into these low-lying areas likely increased deep recharge at those locations and resulted in wetter conditions in the BC sedimentary interbeds within the SDA. In addition, digging of pits and trenches in the SDA also destroyed the natural soil layering and probably facilitated infiltration at those locations (Barraclough et al. 1976).

With the exception of 76-5, the wells inside the SDA that monitor BC interbed sediments were located near or adjacent to the drainage ditches along the main east-west road through the SDA and thereby provide a limited view of the subsurface regime. Well 76-5, located away from the main road, has a lower average water potential (-140 cm of water) similar to those of the outside wells. The higher moisture observed in the BC sediments at wells near the road did not occur at well 76-5, suggesting lateral spreading of moisture did not extend as far as 76-5, located approximately 115 m north of the main east-west road. However, this hypothesis is based solely on a single location. To evaluate this hypothesis further, deep sedimentary interbed monitoring locations in the SDA away from the main road and drainage ditches would be needed.

Water potential data from the deeper CD sedimentary interbed (shown by open squares in Figure 9) are limited and yield mixed results. There are only two deep tensiometers (O4-69 and O3-67) in the deeper CD sedimentary interbed that are located outside the SDA. These two tensiometers yielded both the highest and the lowest water potentials within the CD sedimentary interbed. The most negative (relatively driest) average water potential within the CD interbed (-376 cm of water) was at tensiometer O4-69. The tensiometer at O3-67 yielded the wettest average water potential of -122 cm of water. These mixed results, along with the limited number (two) tensiometers located outside the SDA in the CD interbed sediments, preclude making a similar comparison of moisture conditions inside to outside the SDA at this depth.

3.2.2 Comparison of Water Potentials Between the BC and CD Sedimentary Interbeds

Average water potentials shown in Figure 9 are higher in the BC interbed sediments, both inside and outside the SDA, than in the CD interbed sediments. Average water potentials in the BC interbed range from -43 to –207 cm of water, with a mean of -128 cm of water, whereas average water potentials in the CD interbed range from -122 to -376 cm of water, with a mean of -248 cm of water. Water potential data along a vertical profile, from wells and well pairs that monitor both the BC and CD sedimentary interbeds (I-1S and I-1D, I-2S and I-2D, I-3S and I-3D, I-4S and I-4D, and O-4), show higher water potentials in the BC interbed sediments than in the deeper CD interbed sediments (Figure 10).

A homogeneous porous medium would be expected to exhibit constant water potentials over the vertical profile under unsaturated, steady-state, one-dimensional flow conditions. However, the RWMC is a highly heterogeneous system, containing thick basalt sequences intercalated with lithologically different sedimentary interbeds. Varying water potentials over the vertical profile would be expected in such a heterogeneous system. In a heterogeneous system under unsaturated, steady state flow conditions, Yeh (1989) suggests pressure head (water potential) values will vary over the vertical profile to maintain a constant flux. The inherent characteristic hydraulic properties of a particular lithology will determine the water potential required to maintain the constant flux.

Soil type and texture may strongly control the water potential differences observed between the BC and CD sedimentary interbeds, but other factors could potentially have an influence. The BC sedimentary interbed is the first continuous sedimentary interbed encountered by surface recharge. As such, the BC interbed sediments probably dampen and store episodic recharge, controlling the deep flux into basalts below the BC sedimentary interbed.

There is also a possibility that lateral flow from the spreading areas could move substantial amounts of water into the sediments in the BC or CD interbeds, causing the observed water potential differences. There are no trends in the water potential data that would suggest wetter conditions nearer the spreading areas in either the BC or CD sedimentary interbeds. However, water has not been discharged to the spreading areas in over three years. Monitoring during periods of discharge to the spreading areas over a more complete vertical profile would be needed to evaluate the influence of the spreading areas on the water potentials of the BC or CD sedimentary interbeds.

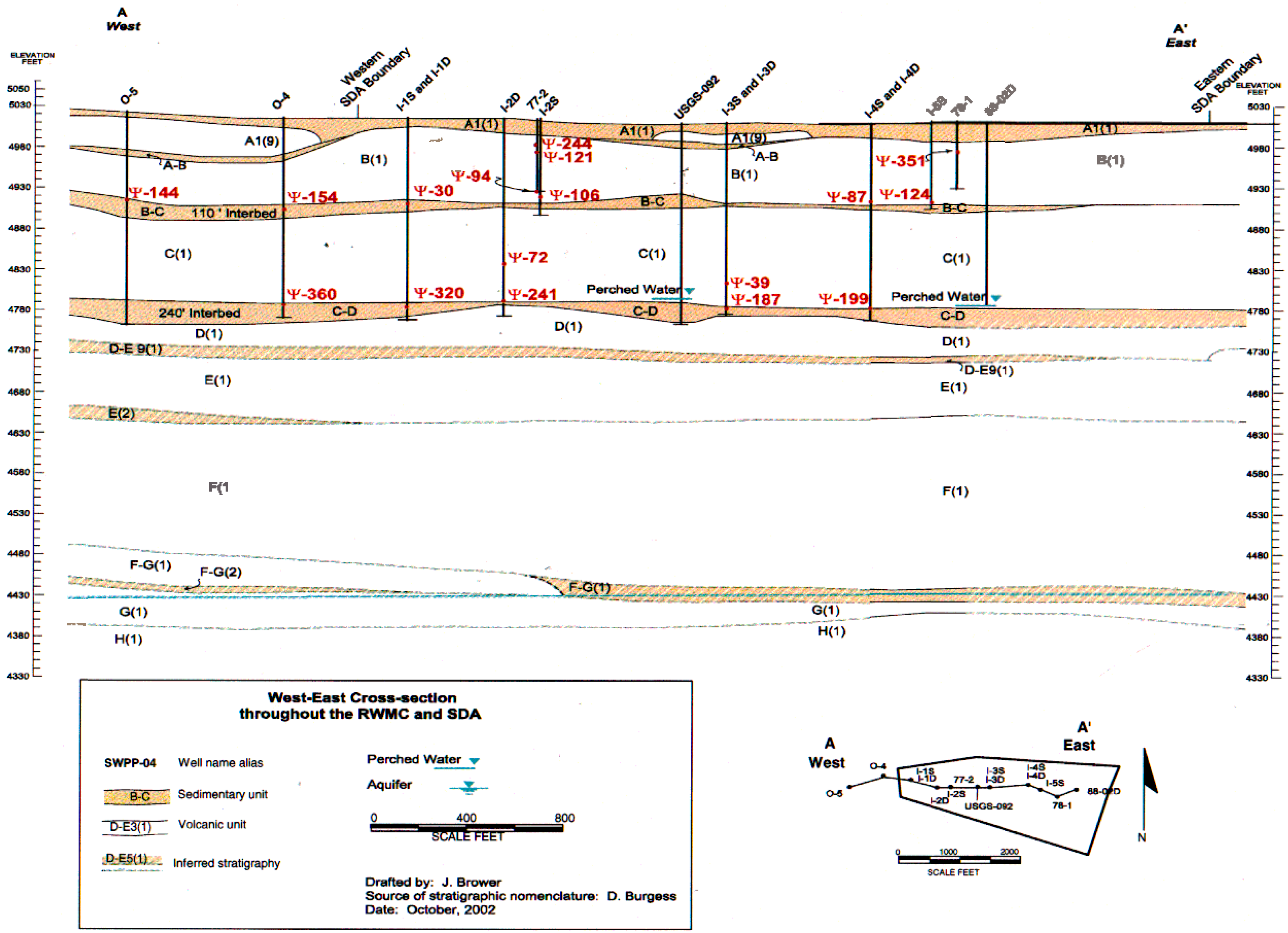

Figure 10. East-west cross section across the Subsurface Disposal Area, comparing average water potentials in the BC and CD sedimentary interbeds.

3.2.3 Basalt Water Potentials With Depth

A comparison of average water potentials in the basalts shows a strong trend of increasing water potential (increasing moisture) with depth, to the CD sedimentary interbed. Water potential data for basalts extend only to the top of the CD sedimentary interbed. The average water potentials for the basalt (shown by red triangles in Figure 9) range from -351 cm of water at 10.7 m in well 78-1 to saturation (0+ cm of water) at perched water wells at USGS-92 and 8802D, located in the basalt, just above the CD sedimentary interbed.

One hypothesis that may help explain the increased moisture in the deeper basalt, below the BC sedimentary interbed, is the movement of water from the spreading areas to the SDA. The spreading areas (Figure 1) are located 1.6 km west and 1.1 km southwest of the SDA. These infiltration basins hold water diverted from the Big Lost River during periods of high flow. Water from the spreading areas may move downward and laterally, in a stepwise fashion, into the basalts above the CD sedimentary interbed, in the SDA.

There is evidence to suggest the spreading areas are a source of perched water in basalt above the CD sedimentary interbed, in the SDA. An isotopic analysis of perched water at USGS-92 (Rightmire and Lewis 1987) suggests the spreading areas are a source for perched water in basalt, above the CD sedimentary interbed in USGS-92. Hubbell (1990) also suggests the spreading areas are one of the sources of perched water in USGS-92 because of perched water level responses to the presence of water in the spreading areas. More recently, the movement of water from the spreading areas to the SDA was documented by the arrival of a naphthalene sulfonate tracer in perched water at USGS-92, less than 91 days after introduction of the tracer into the spreading areas (Nimmo et al. 2002).

Nimmo et al. (2002) hypothesize that flow from ponded infiltration is predominately vertical, and occurs through discontinuities in low-permeability layers (such as dense basalt or fine-grained sediments). However, these low-permeability layers do cause some perching and lateral diversion of water through basalt fractures, rubble zones, or other high permeability features. Based on the results of the tracer experiment, the nature of this lateral diversion is not uniform with direction. Tracer was detected, at the BC interbed level, at seven wells approximately 1.3 km east of Spreading Area B, but tracer was not detected at the BC interbed level in V-10, in the SDA, approximately 1.3 km north of Spreading Area B. Tracer was detected in basalt above the CD sedimentary interbed in USGS-92 in the SDA. If the low permeability layer at the BC interbed level was not continuous in the direction of the SDA, spreading area water may have moved below the BC sedimentary interbed into high-permeability features in the C basalts above the CD sedimentary interbed and moved at least partially in the direction of the SDA.

The trend of increasing water potentials with increasing depth in the basalt does not confirm movement of water from the spreading areas to the SDA, but it is consistent with the hypothesis of stepwise vertical and lateral water movement from the spreading areas to the deeper basalts. Water potentials in the C basalts above the CD sedimentary interbed show saturated and near-saturated conditions, which may be the result of stepwise flow from the spreading areas reaching the SDA through the C basalts. This is consistent with a lack of tracer detection in the B basalts at V-10 and a positive detection of tracer at USGS-92 in the C basalts. Water potential data from the tensiometer monitoring network are needed during periods when Big Lost River water is discharged to the spreading areas to provide corroboration.

The influence of spreading areas on water potentials in the CD interbeds has not been determined. Water potentials in the BC sedimentary interbed are greater than or equivalent to water potentials in the B basalts (located above the BC sedimentary interbed). In contrast, water potentials in the CD sedimentary interbed are lower than the water potentials in the saturated and near-saturated C basalts above the CD interbed. The current monitoring network is not sufficient to address this difference. Locations of the current monitoring sites do not provide water potential data in the CD sedimentary interbed directly below the saturated and near-saturated basalts. Water potential data are needed from vertical profiles, rather than from multiple wells, to determine if low water potentials occur in sediments beneath the saturated or near-saturated basalts.

3.2.4 Summary and Recommendations Relative to Spatial Comparisons

Water potential data in the BC sedimentary interbed suggest wetter conditions inside the SDA than outside the SDA. This is attributed to focusing of flow to low-lying areas inside the SDA, such as drainage ditches or open pits or trenches that collect run-off from snowmelt and high intensity rains.

The range of average water potentials in the BC sedimentary interbed (-43 to –207 cm of water) was higher than the range of average water potential in the CD sedimentary interbed (-122 to 376 cm of water). Soil type and texture may exert the greatest influence on the water potential differences, but other factors may have an influence. Proximity of the BC sedimentary interbed to surface recharge could increase water potentials in the interbed. There is also the possibility lateral flow from the spreading areas could influence the water potentials exhibited by either the CD or BC interbed sediments.

A trend of increasing water potentials with increasing depth was noted in the basalts. This is consistent with the hypothesis of stepwise vertical and lateral water movement from the spreading areas to the deeper basalt. Water potential data from the tensiometer monitoring network are needed during periods of standing water in the spreading areas to provide corroboration.

Advanced tensiometer monitoring over a vertical profile that extends from near the surface to below the CD interbed is needed to track surface infiltration events and subsurface lateral flow from the spreading areas. Monitored depths should include a basalt profile above and below the BC and CD sedimentary interbeds and several locations within the sedimentary interbeds. Monitoring wells at and below the depth of the CD sedimentary interbed are needed in proximity to drainage ditches, and in locations further away from the main road, to determine the extent of lateral spreading of moisture at depth and the influence of the drainage ditches. The effects of lateral flow from the spreading areas should also be considered when siting these intensely monitored vertical profiles.

3.3 Deep Percolation

Deep percolation is the water that moves downward beneath the influence of evapotranspiration and becomes ground water recharge when it reaches the water table. The rate of deep percolation can be estimated from the advanced tensiometer data, in conjunction with hydraulic properties data, using a unit gradient approach. In this section, water potentials from the deep tensiometers are used to determine if unit gradient conditions occur in the subsurface at the RWMC. Advanced tensiometer and hydraulic properties data are then used to estimate deep percolation.

3.3.1 Unit Gradient

Water potential values from the deep tensiometers can be used to calculate percolation in the deep vadose zone, assuming a unit gradient exists and saturated and unsaturated hydraulic conductivities are known. A unit gradient exists when there is little-to-no change in water potential with respect to depth or elevation, resulting in a hydraulic gradient of one. Assuming one-dimensional, vertical flow, Darcy's Law states:

$$q = -K(\Psi)\ (dH/dZ)$$

where q is the flux $K(\Psi)$ is the hydraulic conductivity as a function of water potential, and dH/dZ is the hydraulic gradient. The hydraulic gradient, dH/dZ, is composed of both water and elevation potentials such that

$$dH/dZ = d\Psi/dz + dz/dz\ .$$

If there is no change in water potential with depth, then the change in total head is only due to changes in elevation and the hydraulic gradient is one, or unity. Under these conditions, the flux, or deep percolation rate, equals the hydraulic conductivity at the specified water potential.

It is recognized that there are limitations in applying the unit gradient method to the tensiometer data. The tensiometers are widely spaced over an approximately 1 km^2 area and do not represent a true vertical profile. Local gradients within the interbeds cannot be determined from this tensiometer array. The unsaturated subsurface at the RWMC is heterogenous and is not an ideal, one-dimensional, steady state flow system. Episodic infiltration events occur at the surface that may extend to the depth of the BC interbed. Long-term drying and wetting trends were observed at some of the deeper tensiometers There is a potential for subsurface lateral flow from the spreading areas to the SDA, lateral flow along sloping surfaces and local discontinuities, and water may take indirect paths through basalt fractures.

However, application of the unit gradient method does have some validity. The lack of water in the spreading areas and lower-than-average precipitation during this time period (spring 2000 through September 2002) decreased the potential impact of infiltration events at the surface or lateral flow from the spreading areas. No infiltration events were recorded at these monitored locations during this time period. The majority of the deeper (17 m or deeper) tensiometers did show steady state conditions. Those tensiometers that showed transient conditions exhibited long-term trends over a 2-1/2 year period. A previous investigation (Hubbell et al. 2002) provided advanced tensiometer data along a 31-m vertical profile, at 76-5, to show near-unit gradient conditions at that location.

The average water potential data listed in Table 1 were used to calculate hydraulic head (the sum of the average water potential, in meters, and the elevation head) and plotted versus elevation in Figure 11. The hydraulic gradient, or change in hydraulic head versus elevation is close to one, indicating unit gradient exists in the upper 73 m of the unsaturated subsurface at the SDA.

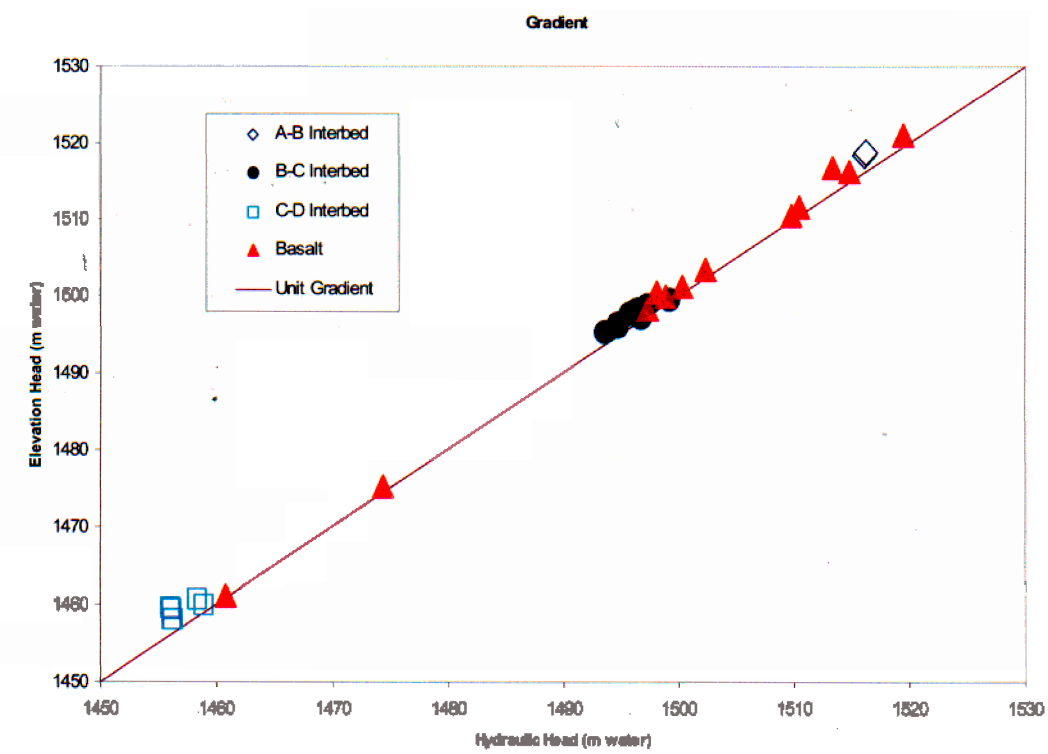

Figure 11. Slope of elevation head versus hydraulic head is near one, indicating unit gradient conditions over the upper 73 m of the unsaturated zone in the subsurface in and around the Subsurface Disposal Area.

3.3.2 Estimate of Steady-State Flux

Average water potentials from the sedimentary interbeds will be used to estimate deep percolation at steady state. Under unsaturated conditions, it is assumed the sedimentary interbeds control the percolation of water at depth. The BC and CD sedimentary interbeds are extensive and generally continuous in this area, and the sediments in the interbeds provide a mechanism to dampen and average the moisture over distance, as opposed to the channeling of moisture that may occur in fractured basalt. Also, the sedimentary interbeds provide a porous medium to which Darcy flow can be applied.

Magnuson and McElroy (1993) developed representative moisture characteristic curves from sedimentary interbed data sets, using Θ_r, α, and n as the fitting parameters and averaged K_s and Θ_s values. The researchers used van Genuchten's (1980) formulations, based on Mualem's (1976) theoretical model, to estimate hydraulic parameters for sedimentary interbed data sets. The equations used were as follows:

$$\Theta_v = \Theta_r + (\Theta_s - \Theta_r)\,(1 + (\alpha\Psi)^{n})^{-m} \tag{1}$$

and

$$K(S^*) = K_s\,(S^*)^{1/2}\,(1 - (1 - S^{*\,1/m})^{m})^2 \tag{2}$$

where

Θ_v = volumetric moisture content (cm^3/cm^3)

Θ_s = saturated moisture content (cm^3/cm^3)

Θ_r = residual moisture content (cm^3/cm^3)

α = inverse of air entry potential (1/cm)

Ψ = water potential (cm)

n = fitting parameter (dimensionless)

$m = 1 - 1/n$

K_s = saturated hydraulic conductivity (cm/s)

$S^* = (\Theta_v - \Theta_r) / (\Theta_s - \Theta_r)$.

Magnuson and McElroy (1993) developed representative moisture characteristic curves from sedimentary interbed data sets, using Θ_r, α, and n as the fitting parameters and averaged K_s and Θ_s values. Hydraulic parameters for two separate representative moisture characteristic curves are shown in Table 2. Based on geologic descriptions, sediments at the advanced tensiometer locations in the BC interbed were generally sands, sandy silts, and sandy gravels. Therefore, hydraulic parameters for the BC sedimentary interbed in Table 2 were based on two core samples of sand-sized sediment. Values for the CD sedimentary interbed in Table 2 were based on five predominantly silt-sized samples, typical of the lithology reported at tensiometer locations in the CD interbed in Settle and Dooley (2002).

Table 2. Hydraulic parameters from Magnuson and McElroy (1993) based on representative moisture characteristic curves.

	K_s (cm/s)	Θ_s (cm^3/cm^3)	Θ_r (cm^3/cm^3)	α (cm^{-1})	n
BC Interbed	6.25E-03	0.48	0.043	0.031954	2.5338
CD Interbed	1.525E-04	0.57	0.14	0.017751	1.3753

Water content and hydraulic conductivity as a function of water potential, [$\Theta(\Psi)$ and $K(\Psi)$, respectively], were then calculated using the parameters from the representative moisture characteristic curves in Table 2. The estimated water content and hydraulic conductivity at the averaged water potentials are shown in Table 3 at each advanced tensiometer location in the BC and CD sedimentary interbeds.

Moisture content estimates in Table 3 suggest the effects of nonuniform infiltration in the SDA through ditches, open pits or trenches, or other topographically low areas are evident in the BC interbed sediments but are not evident in the CD sediments. Within the SDA, moisture contents for the BC interbed varied from 8 to 35%; whereas estimates in the CD interbed (within the SDA) varied by only 4%, ranging from 36 to 40%. Moisture content variations observed in the BC interbed, within the SDA, were greater than those in the deeper CD sedimentary interbed. These results suggest nonuniform surface infiltration patterns within the SDA extend to the depth of the BC sedimentary interbed, through predominantly vertical flow, but do not extend to the CD sedimentary interbed. The BC interbed sediments may dampen and store the episodic recharge, controlling the deep flux into basalts beneath the sediments. Under these conditions, moisture content estimates in the CD sedimentary interbed and BC interbed sediments outside the SDA may be more representative of long-term, steady-state flow conditions than moisture content estimates from BC interbed sediments inside the SDA.

It is possible that moisture content variations within the CD interbed were masked by lateral flow from the spreading areas. If this were the case, a trend of higher moisture contents closer to the spreading areas would be expected, rather than the more uniform moisture content distribution exhibited in the CD sedimentary interbed. On the other hand, water has not been discharged to the spreading areas in over three years and the effects of the lateral flow are merely speculative. Monitoring during periods of discharge to the spreading areas over a more complete vertical profile would be needed to evaluate the influence of the spreading areas on the water potentials of the BC or CD sedimentary interbeds.

Under unit gradient conditions, the unsaturated hydraulic conductivity, which is a function of water potential, equals the deep percolation at the corresponding water potential. These deep percolation estimates (P, expressed in units of cm/yr) are listed in Table 3, and represent the deep recharge at each monitored location in the BC and CD sedimentary interbeds. The percolation estimates ranged from 1.4 to 21,539 cm/year.

As suggested earlier in this section, deep percolation rates based on BC sedimentary interbeds within the SDA may not be representative of long-term steady state moisture conditions. The highest estimates of 21,539 and 8325 cm/yr were both from BC interbed sediments within the SDA. They do not appear to be physically realistic for the subsurface beneath the RWMC, and a buildup of moisture above low conductivity materials may have caused the high water potentials. It is also possible the simplifying assumptions of unit gradient conditions or a homogeneous sand unit to represent the BC sedimentary interbed were not applicable at those locations.

Table 3. Estimated moisture contents $\Theta(\Psi)$, hydraulic conductivities $K(\Psi)$, and rates of deep percolation (P) at average water potentials (Ψ), for each advanced tensiometer location in the BC and CD sedimentary interbeds. Values from inside the Subsurface Disposal Area are shaded.

Well	Average Ψ (cm water)	Θ (Ψ) (cm^3/cm^3)	K (Ψ) (cm/s)	P or K(Ψ) (cm/yr)
BC Sedimentary Interbed				
I1S	-30	0.35	6.83E-04	21539
I3S	-39	0.28	2.64E-04	8325
I4S	-87	0.13	5.12E-06	161
I5S	-124	0.09	7.02E-07	22.1
76-5	-161	0.08	1.57E-07	5.0
O2	-131	0.09	5.13E-07	16.2
O5	-144	0.08	2.99E-07	9.4
O4	-154	0.08	2.03E-07	6.4
O1	-180	0.07	8.26E-08	2.6
O7	-195	0.07	5.20E-08	1.6
CD Sedimentary Interbed				
I3D	-187	0.40	2.60E-07	8.2
I4D	-199	0.40	2.21E-07	7.0
I2D	-240	0.38	1.34E-07	4.2
I1D	-320	0.36	6.09E-08	1.9
O3	-109	0.45	1.00E-06	31.5
O4	-360	0.35	4.39E-08	1.4

Under the assumption that percolation rates most representative of steady-state flow conditions are based on moisture content estimates from the CD sedimentary interbed and from BC interbed sediments outside of the SDA, the deep percolation estimates ranged from 1 to 32 cm/yr. The 1 to 32 cm/yr range appears to be reasonable, given the average annual precipitation of 22 cm, the potential for focused infiltration on the SDA, and the simplifying assumptions used to estimate the percolation rates. These simplifying assumptions include the use of the unit gradient approach, the lack of field data to determine local gradients within sedimentary interbeds, and assigned homogeneity and soil type for the sedimentary interbeds.

For comparison, Magnuson and McElroy (1993) estimated 4 to 10 cm/yr of deep percolation beneath the SDA, using the unit gradient approach and assuming a homogeneous sedimentary interbed. However, their estimates were based on single point-in-time, in situ moisture contents from interbed core, rather than the long-term, field water potentials used in the analyses in this report.

3.3.3 Summary and Recommendations Relative to Deep Percolation

Moisture content estimates within the SDA show greater variability in the BC interbed sediments as compared to the CD interbed sediments. These results suggest nonuniform surface infiltration patterns within the SDA extend to the depth of the BC sedimentary interbed, through predominantly vertical flow, but do not extend to the CD sedimentary interbed. The BC interbed sediments may then dampen and store the episodic recharge, controlling the deep flux into basalts beneath the sediments. Under these conditions, moisture contents in the CD sedimentary interbed and BC interbed sediments outside the SDA may be more representative of long-term, steady-state flow conditions than moisture contents from BC interbed sediments inside the SDA.

Deep percolation through the BC and CD sedimentary interbeds was estimated from averaged water potentials, using a unit gradient approach. Under the assumption that percolation rates most representative of steady-state flow conditions were based on moisture content estimates from the CD sedimentary interbed and from BC interbed sediments outside of the SDA, percolation estimates ranged from 1 to 32 cm/yr. The 1 to 32 cm/yr range appeared to be reasonable, given the average annual precipitation of 22 cm, the potential for focused infiltration on the SDA, and the simplifying assumptions used to estimate deep percolation.

These estimates of deep percolation rely on hydraulic property data from a limited set of core collected before 1989. Additional hydraulic property data are available from interbed core collected and analyzed in Fiscal Year 2000 (Settle and Dooley 2002). This additional data should be used to augment estimates of deep percolation. However, an initial review of the interbed core data determined the core were sieved and repacked for determination of moisture characteristic curves, which disturbs the sample and may influence the results. The appropriate use of this data should be determined.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Water potential data from a network of 30 deep advanced tensiometers were evaluated to determine the appropriateness of the current conceptual model of flow and thereby increase confidence in the numerical representation of flow at the RWMC. The advanced tensiometer monitoring data supported and expanded upon assumptions in the conceptual model of flow in the unsaturated zone at the RWMC. In addition, the monitoring network provided data for hydrologic flow model calibration and prediction as well as baseline water potential data for use in evaluating remediation activities.

Temporal and spatial water potential trends, moisture distribution, and deep percolation rates were evaluated in basalts and sediments beneath the RWMC. The network of advanced tensiometers provided approximately 2-1/2 years of water potential data in basalts and sedimentary interbeds from 6.7 to 73.5 m bls. The majority of the advanced tensiometer locations have been monitored since spring 2000. However, advanced tensiometers in three of the 18 wells have been monitored since 1996, providing over six years of water potential data.

The following observations were made regarding moisture movement at depth. Numerical simulation results can be compared to these observations to determine the appropriateness of the modeling applications.

Measured water potentials from spring 2000 through August 2002 ranged from near saturation (-30 cm of water) in the BC interbed sediments near the main road through the SDA, to –400 cm of water in the CD interbed sediments, outside of the SDA.

Water potential data from the majority of the deepest (17 m or greater) advanced tensiometer locations indicated little-to-no change in moisture, suggesting steady state conditions existed at those locations for the past 2-1/2-year monitoring period. These advanced tensiometers were in sediments and basalts at or below the 17-m depth and tended to be located in wells farthest from the main east-west road through the SDA.

Long-term drying trends were noted in some sediments and basalts. The largest overall decrease in water potentials occurred in the shallower sediments and basalts above the 12-m depth. These shallower depths may be responding to decreased infiltration at the surface, from the cumulative effect of less-than-average annual precipitation for the last three years (2000 through 2002). Long-term drying of deeper sediments also occurred in the BC interbed sediments at I3S-28, I4S-30, and O4-34 and in the CD interbed sediments at I1D-69, I3D-70, and I4D-69. Wells showing long-term drying trends are those located nearest the drainage ditches that parallel the main east-west road through the SDA. These drainage ditches likely focused surface infiltration during years of high run-off from snowmelt. The long-term drying trends in sediments at wells near these drainage ditches may be in response to decreased run-off from three years of less-than-average precipitation (2000 through 2002).

No episodic recharge events were recorded at these monitoring locations during the spring 2000 through August 2002 time period. However, this monitoring system has not yet experienced a significant precipitation year, and the results are preliminary. Episodic infiltration events were detected at two monitored locations in spring 1999, to the 17.3-m depth at 76-5 (McElroy and Hubbell 2001; Hubbell et al. 2002), and to at least the 10-m depth at 77-2. Since the 1999 infiltration event, basalts and sediments at 76-5 and 77-2 that were affected by the episodic recharge have shown long-term drainage. Water potentials in the shallower (less than 10-m) depths at 76-5 have decreased to less than the pre-1999 values.

Average water potentials in the BC interbed sediments suggested wetter conditions inside the SDA compared to outside the SDA. This was attributed to focusing of flow to low-lying areas inside the SDA, such as drainage ditches or open pits or trenches that collect run-off from snowmelt and high-intensity rains.

Moisture content estimates within the SDA showed greater variability in the BC interbed sediments as compared to the CD interbed sediments. These results suggested nonuniform surface infiltration patterns within the SDA extended to the depth of the BC sedimentary interbed, through predominantly vertical flow, but did not extend to the CD sedimentary interbed. The BC interbed sediments may have dampened and stored the episodic recharge, controlling the deep flux into basalts beneath the sediments. Under these conditions, it was suggested that moisture contents in the CD sedimentary interbed and BC interbed sediments outside the SDA were more representative of long-term, steady-state flow conditions than moisture contents from BC interbed sediments inside the SDA.

Deep percolation through the BC and CD sedimentary interbeds was estimated from averaged water potentials, using a unit gradient approach. Under the assumption that percolation rates most representative of steady-state flow conditions were based on moisture contents from the CD sedimentary interbed and from BC interbed sediments outside of the SDA, percolation estimates ranged from 1 to 32 cm/yr. The 1- to 32-cm/yr range appeared to be reasonable, given the average annual precipitation of 22 cm, the potential for focused infiltration on the SDA, and the simplifying assumptions used to estimate deep percolation.

The advanced tensiometer monitoring is providing in situ data in the deep subsurface that should remain part of the long-term monitoring strategy at the SDA. Water potential data has proved sensitive enough to discern moisture differences inside and outside the SDA, at depth, thus providing a monitoring reference and baseline to help assess the remediation and closure of the SDA.

4.2 Recommendations

The following recommendation are suggested for the deep advanced tensiometer network:

- **Continue to monitor deep advanced tensiometers to determine subsurface response to infiltration, and potential effects of lateral flow from the spreading area to the SDA.** Locations of advanced tensiometers in the I- and O-series wells were chosen, in part, to determine subsurface response to surface infiltration, and the effects of lateral flow from the spreading areas to the SDA. However, monitoring coincided with below-normal precipitation for the last three years (2000 through 2002) and lack of water in the spreading areas. Monitoring is needed during normal and above-normal precipitation years, as well as during periods of discharge to the spreading areas. This continued monitoring is necessary to establish baseline conditions before emplacement of any infiltration-reducing cap at the SDA.

- **Include new hydraulic property data in deep infiltration assessments and advanced tensiometer data evaluations.** Moisture characteristic curves and hydraulic conductivity data from the Fiscal Year 2000 drilling program were not incorporated into the deep infiltration assessments. The data need to be reviewed to determine their appropriateness, as part of being published. New representative moisture characteristic curves that incorporate the new data should be developed. This would greatly expand the number of samples used in developing representative moisture characteristic curves.

- **A series of wells are needed that are instrumented with nested advanced tensiometers.** The monitoring data from the advanced tensiometer network has improved the conceptual understanding of the movement of water through the subsurface beneath the SDA. While there are some general behaviors that are evident, such as wetter conditions inside the SDA compared to outside the SDA for the BC sedimentary interbed, there is also evidence of complex preferential pathways. To demonstrate ability to monitor contaminant movement in the vadose zone, consideration should be given to expanding the advanced tensiometer network to include a series of wells instrumented with nested advanced tensiometers.

These nested instruments would cover a vertical profile that extends from beneath the surficial sediments into basalt below the CD sedimentary interbed. The vertical profile should include several locations within the interbeds, as well as in the basalt directly above and below the interbeds. In addition, these tensiometers should be located within a small backfill interval that monitors a discrete depth within the profile, rather than the current monitored interval of five to six feet. Several wells should also be instrumented through the entire depth of the vadose zone to the aquifer. When siting new wells, the effects of focused infiltration in the SDA and the influence of lateral flow from the spreading areas should be considered. Appropriate siting and use of nested wells will provide water potential information over the vertical profile to track moisture movement at depth, provide hydraulic gradients within the sedimentary interbeds, provide water potential information between basalt and sediment contacts, provide water potentials in the basalts below the CD sedimentary interbed, determine if substantial lateral flow occurs in the subsurface beneath the SDA, and determine the extent of focused infiltration.

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Appendix A

Well-Construction Diagrams

Appendix A
Well-Construction Diagrams

WELL NAME: 78-1	Easting:	Driller:	Date: 12/19/95
Facility: RWMC	Northing:	Geologist: T. HUMPHREY	Water Level:
Well Type: PERCHED WATER	Longitude:	Drill Method: CORE (PQ)	
Well Status			Water Level Date:
Year Drilled: 1978	Latitude:	Drill Fluid: AIR	
Total Depth 84	Completion Depth: 84	Land Surface:	Water Level Access:

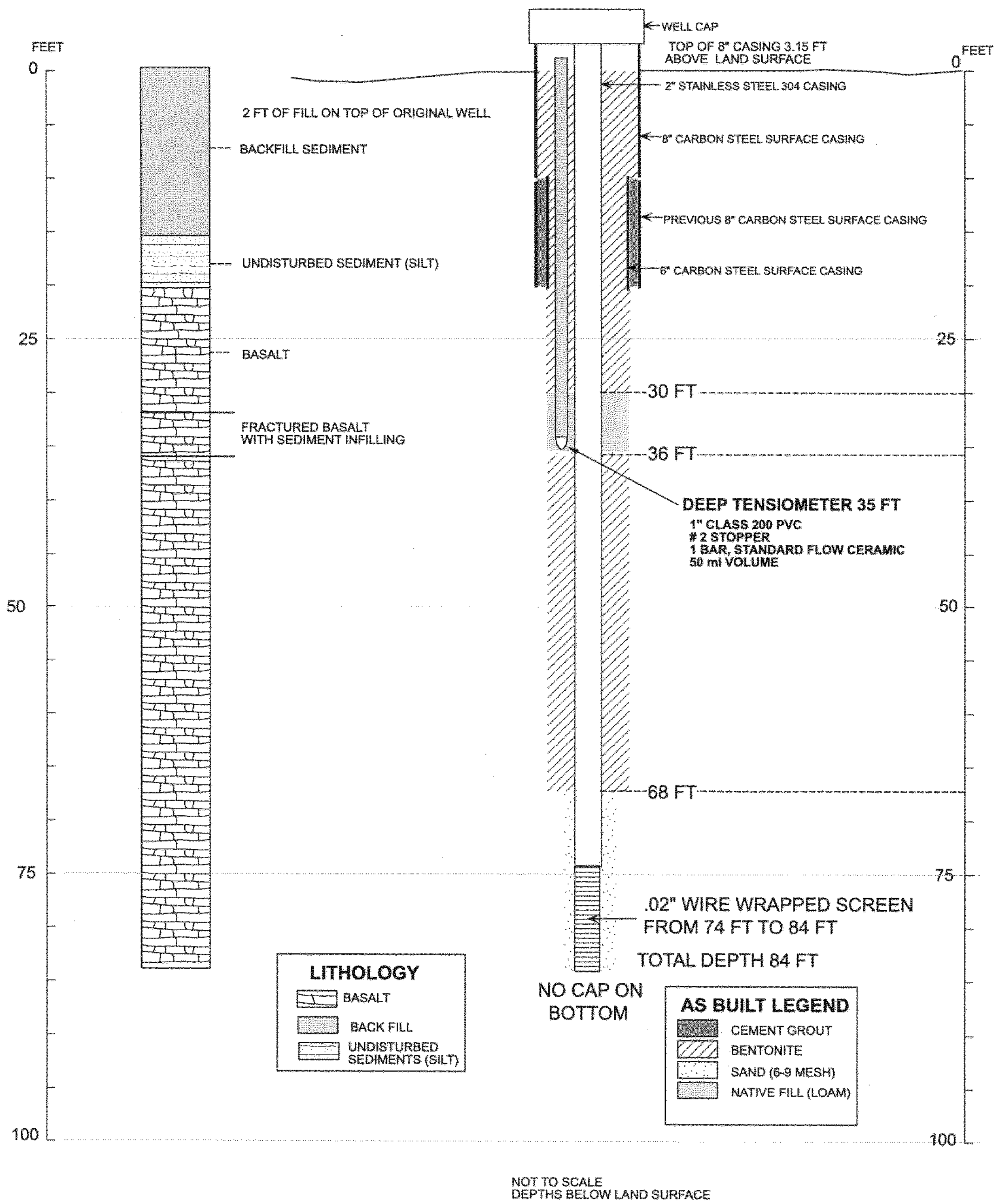

Figure A-1. Well-construction diagram for 78-1.

WELL NAME: 77-2	Easting:	Driller:	Date: 12/19/95
Facility: RWMC	Northing:	Geologist: T. HUMPHREY	Water Level:
Well Type: PERCHED WATER	Longitude:	Drill Method: CORE(PQ)	Water Level Date:
Well Status	Latitude:	Drill Fluid: AIR	
Year Drilled: 1977			
Total Depth 90	Completion Depth: 90	Land Surface:	Water Level Access:

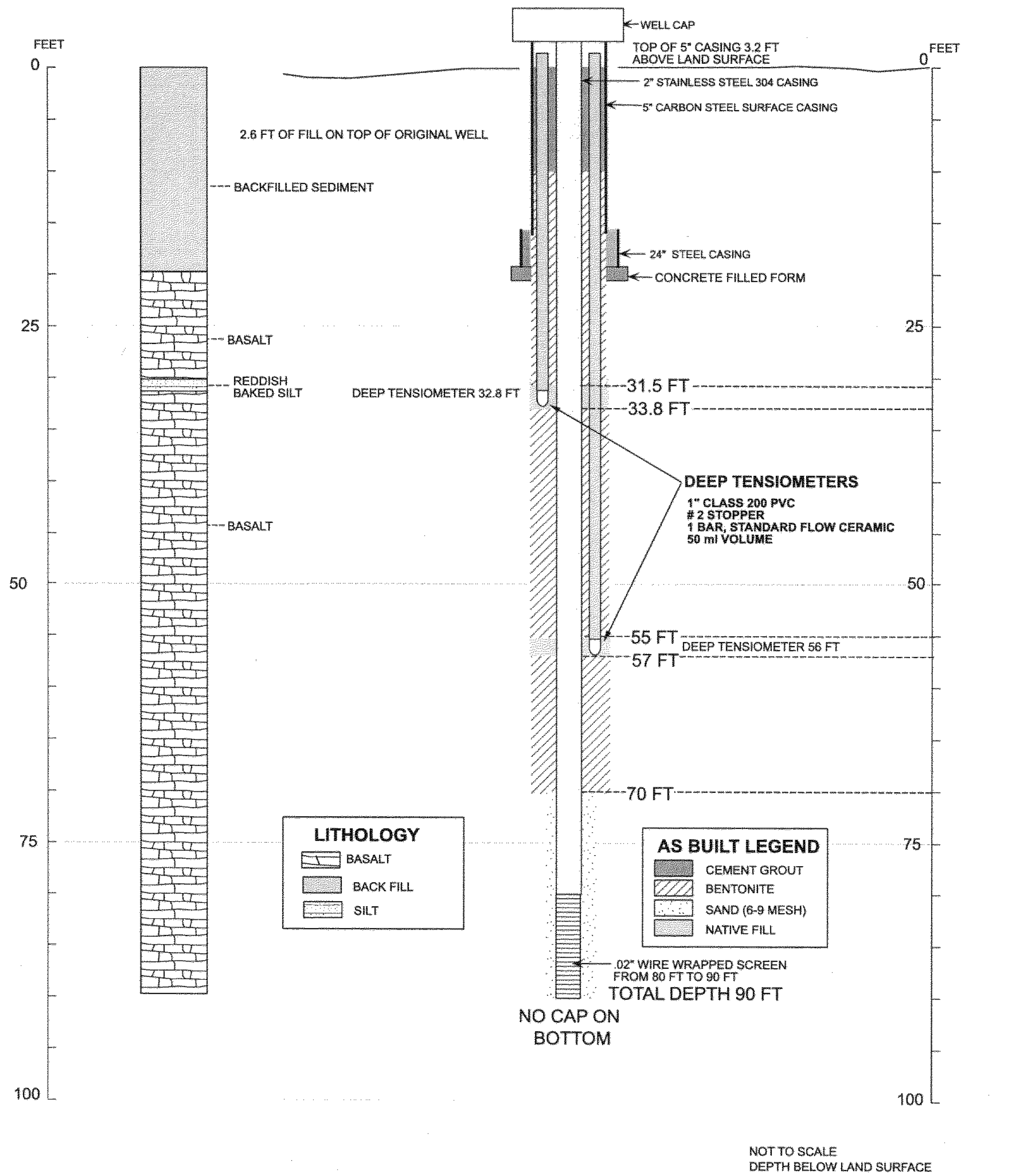

Figure A-2. Well-construction diagram for 77-2.